NASA/CR–2015-218981

Fabrication of Lower Section and Upper Forward Bulkhead Panels of the Multi-Bay Box and Panel Preparation

Final Report

Alexander Velicki, Kim Linton, Krishna Hoffman, Patrick Thrash,
Robert Pickell, and Robert Turley
The Boeing Company, Research and Technology, Huntington Beach California

November 2015

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FABRICATION OF LOWER SECTION AND UPPER FORWARD BULKHEAD PANELS OF THE MULTI-BAY BOX AND PANEL PREPARATION

CONTRACT NNL10AA05B TASK ORDER NNL13AB38T

FINAL REPORT

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THE BOEING COMPANY
BOEING RESEARCH & TECHNOLOGY

PREPARED FOR
NASA LANGLEY RESEARCH CENTER

FOREWORD

This document summarizes work performed by The Boeing Company, through its Boeing Research & Technology group located in Huntington Beach, California under the Environmentally Responsible Aviation (ERA) Project. This report documents the work that was performed between May 9, 2013 and April 10, 2015 to fabricate several large integrated stitched panels and associated hardware, which would ultimately be used to assemble a combined loads fuselage test section to validate the feasibility of a future Hybrid Wing Body (HWB) pressure cabin.

The NASA technical monitor was Ms. Dawn Jegley of the Structural Mechanics and Concepts Branch, NASA Langley Research Center (LaRC).

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Acknowledgment is also made to Ms. Dawn Jegley, Mr. Marshall Rouse, Dr. Adam Przekop and Mr. Andrew Lovejoy, all of NASA-LaRC, for their technical support.

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ACRONYMS

3-D	Three-Dimensional
AJ	Assembly Jig
BHD	Bulkhead
CAPRI	Controlled Atmospheric Pressure Resin Infusion
DA	Determinate Assembly
DMS	Douglas Material Specification
ERA	Environmentally Responsible Aviation
HWB	Hybrid Wing Body
IML	Inner Moldline
MBB	Multi-Bay Box
NDI	Non Destructive Inspection
OML	Outer Moldline
PRSEUS	Pultruded Rod Stitched Efficient Unitized Structure
SoA	State of the Art
TO	Task Order

Introduction

NASA created the Environmentally Responsible Aviation (ERA) Project to explore and document the feasibility, benefits, and technical risk of advanced vehicle configurations and enabling technologies that will reduce the impact of aviation on the environment. A critical aspect of this pursuit is the development of a lighter, more robust airframe that will enable the introduction of unconventional aircraft configurations that have higher lift-to-drag ratios, reduced drag, and lower community noise. The primary structural concept being developed under the ERA program in the Airframe Technology element is the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) structural concept.

The work statement described within this report is a subset of a larger multi-year effort to design, fabricate, and test the Multi-Bay Box (MBB) test article (Figure 1). The detail design, analysis and tool design for the MBB test article was completed under Contract NNL04AA11B, Task Order (TO) NNL10AB00T in 2011. Tooling was procured under Contract NNL04AA11B, TO NNL10AB00T and TO NNL11AA68T, which also included a portion of the overall panel fabrication, acceptance, and nonconformance reporting tasks. Several PRSEUS panels and associated hardware were provided by Contract NNL13AA11C. The remaining panel fabrication work not finished under TO NNL11AA68T was moved to this TO (NNL13AB38T) to be completed and then delivered in the 2013-2014 timeframe (Figure 2).

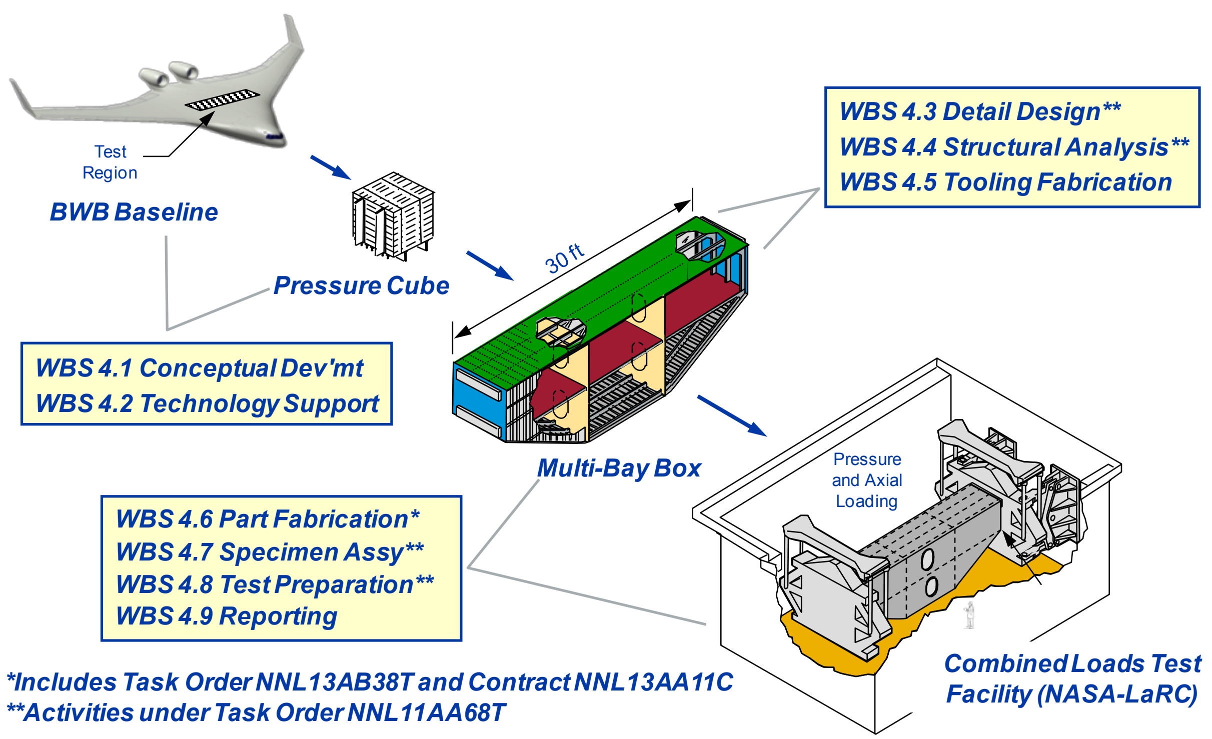


Figure 1. Task Order NNL13AB38T was a Subset of the Overall Multi-Bay Box Development

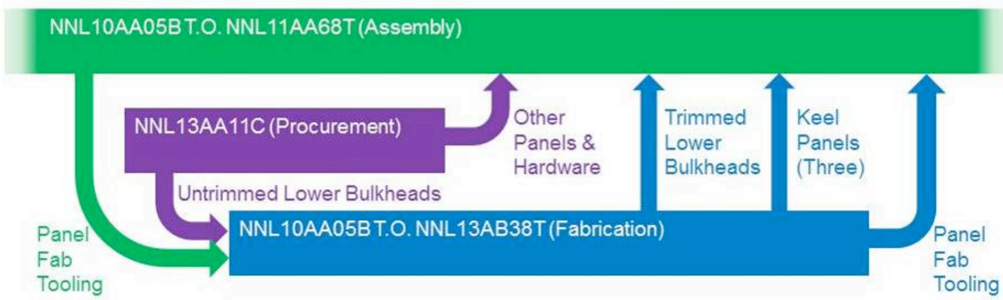


Figure 2. Contract and Task Order Relationships Used to Fabricate MBB Test Article

The panels fabricated under this task order contract comprise the lower section of the box assembly. There are three distinct panel configurations and a left and right-hand unit for the Side Keel and Lower Bulkhead panels (Figure 3). These remaining five panels were in various stages of completion when they were transferred to this task order contract.

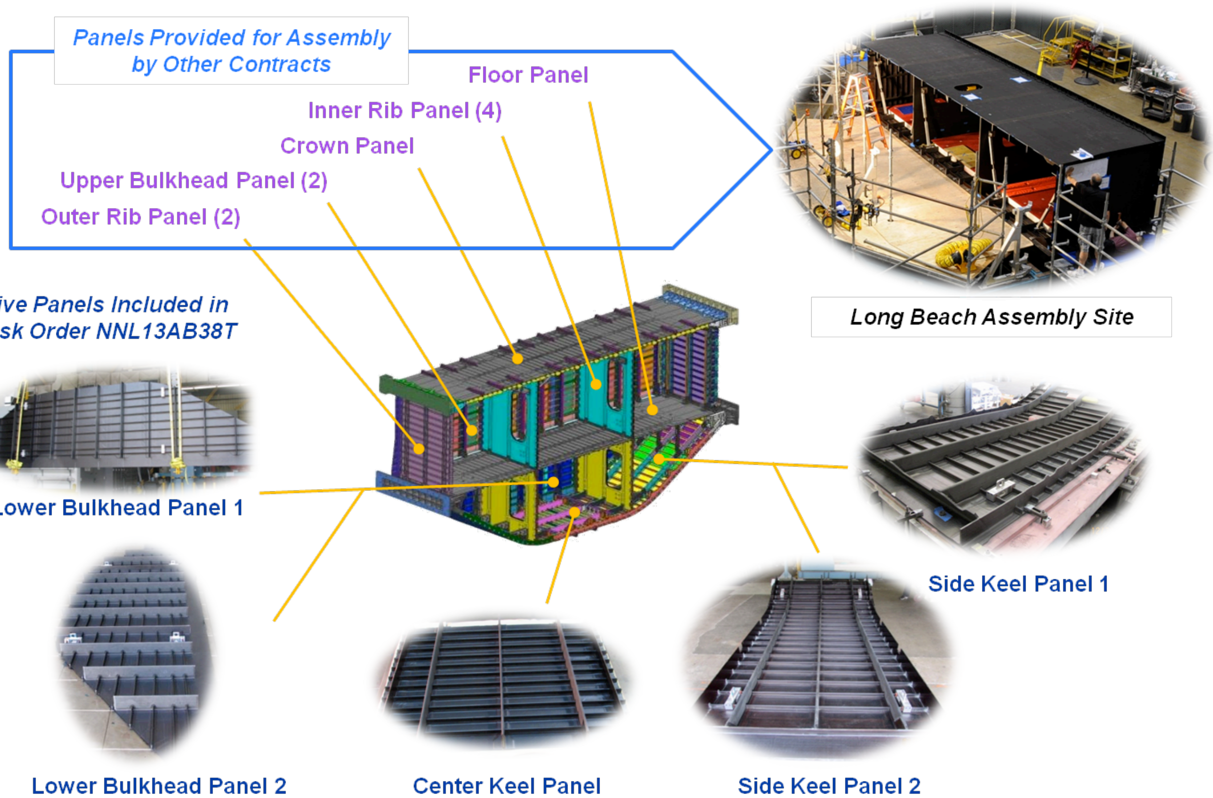


Figure 3. Panel Configurations Included in Task Order NNL13AB38T

Generally, the remaining work to complete panel fabrication fell into two categories: 1) edge trimming and inspection for the cured Lower Bulkhead panels, and 2) panel build up starting with preform assembly for the remaining panels. All of the detail parts (Figure 4) used in these panels were fabricated under Contract NNL13AA11C.

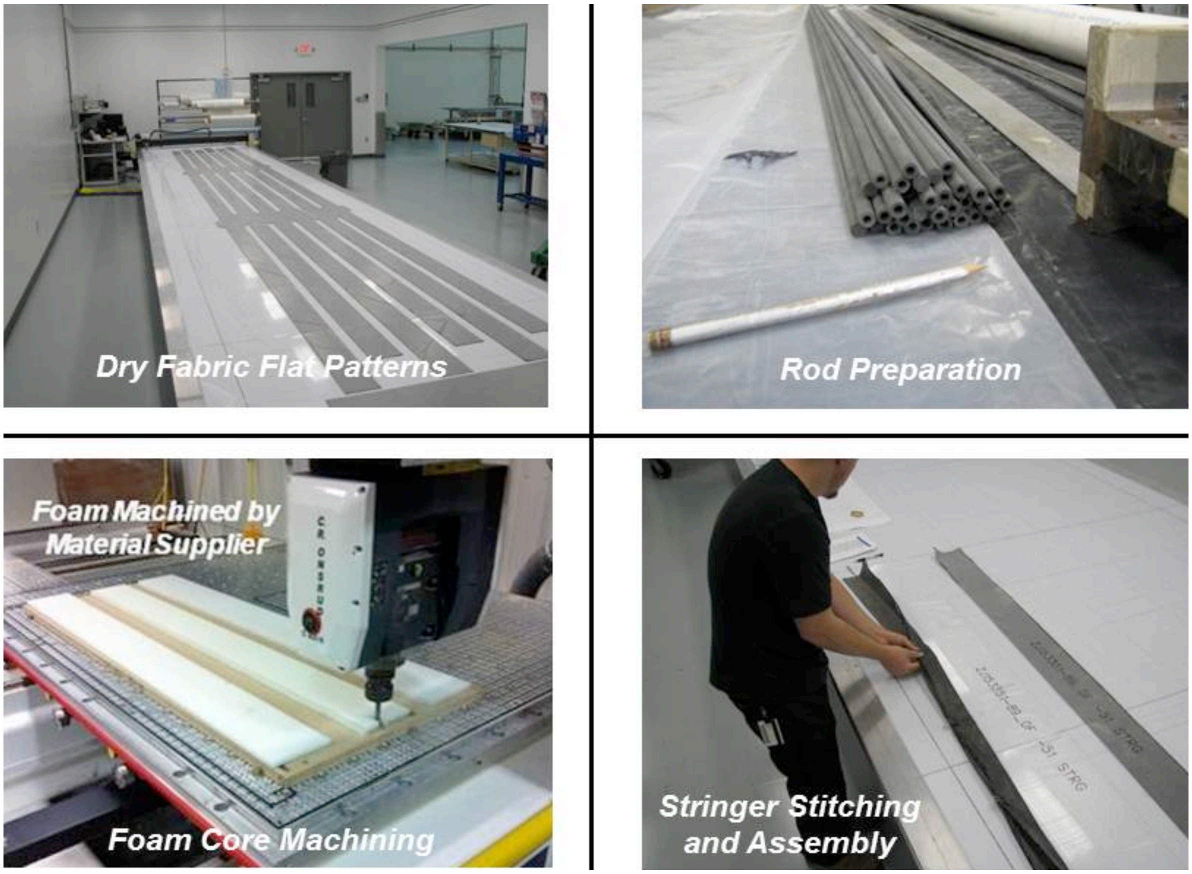


Figure 4. Preform Details Fabricated Under Contract NNL13AA11C

In each case, the panel build up sequence was identical for each of the remaining panel configurations. The prepared warp-knit fabric, foam core details, and rod elements were assembled into the individual preform configurations and then stitched together to create the self-supporting architecture that is positioned onto the cure tool, vacuum bagged, and then infused with resin and cured in the oven using elevated temperature and atmospheric pressures (Figure 5).

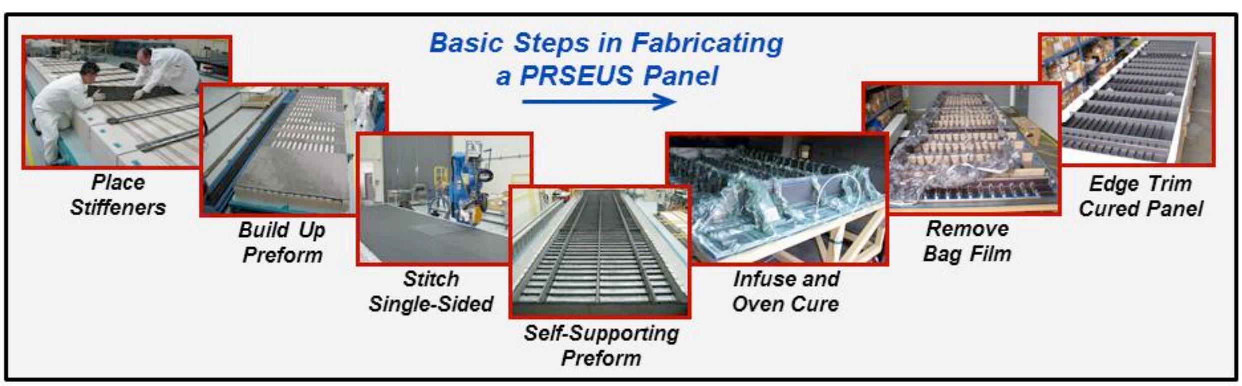


Figure 5. Fabrication Steps to Build a Preform and Cure a PRSEUS Panel

A general overview of the task order work scope and timing is shown in Figure 6.

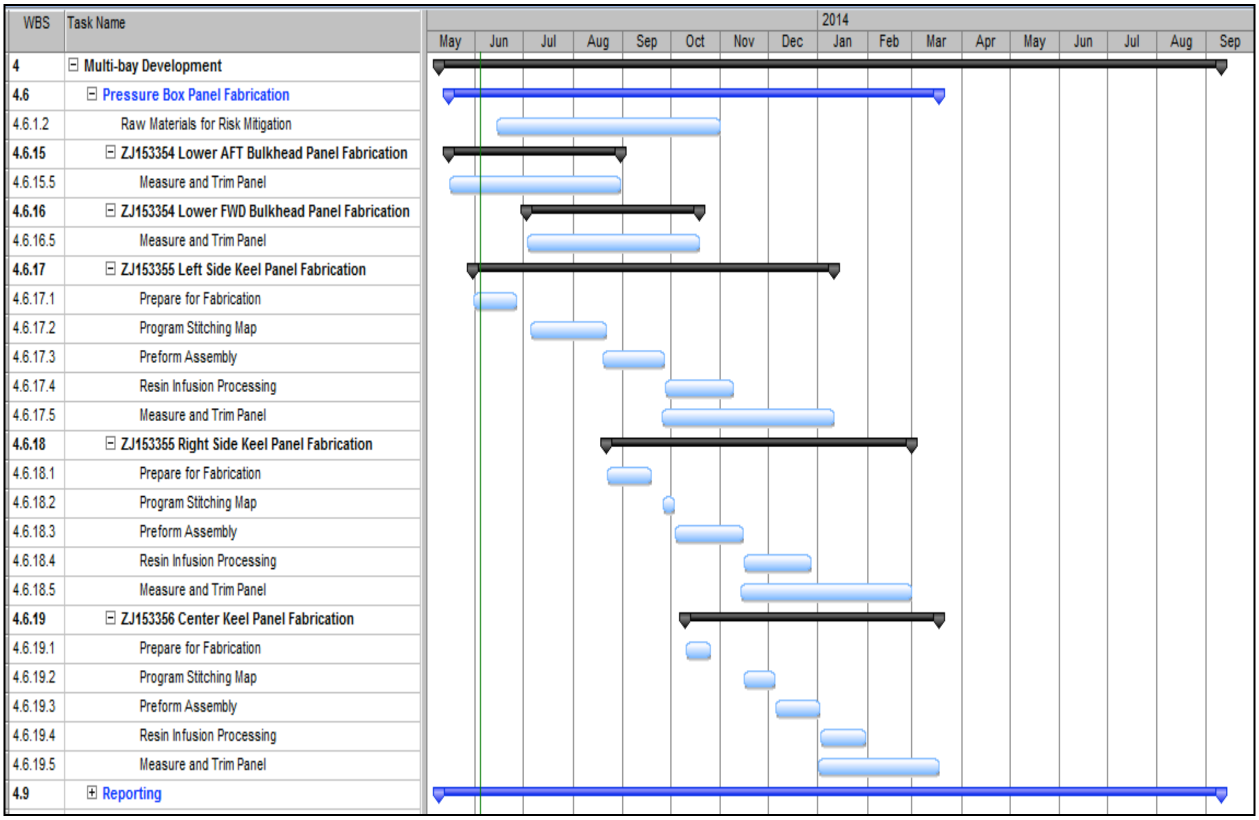


Figure 6. Task Order NNL13AB38T Schedule to Complete Five Panels

After panel fabrication for the MBB was completed, NASA added the fabrication of one additional panel to the scope of this task order. The alternate center keel panel was built as a risk mitigation article, in the event of damage to the MBB requiring a structural patch. The fabrication of the MBB followed the sequence shown in Figure 5, but the panel incorporated some new features, such as foamless frames and modified stitching patterns, which will be described later in this report.

1.0 Lower Bulkhead Panel (Forward and Aft)

The Lower Bulkhead Panel Assembly is comprised of nine stringers, 10 frames, and two integral cap features that support the lower center rib panels (Figure 7). A large access hole is located in the center of the panel to provide access once the box is assembled. The cutout has skin doublers and tapered thicknesses that run out in the adjacent skin bays on the opposite sides of the frames. An integrally machined aluminum cover is mechanically attached to seal the cutout during testing. All of the panel edges and joining regions are thickened beyond minimum gauge skins (.052-inch) to accommodate the mechanical attachments and fittings used to create the pressure-tight box assembly.

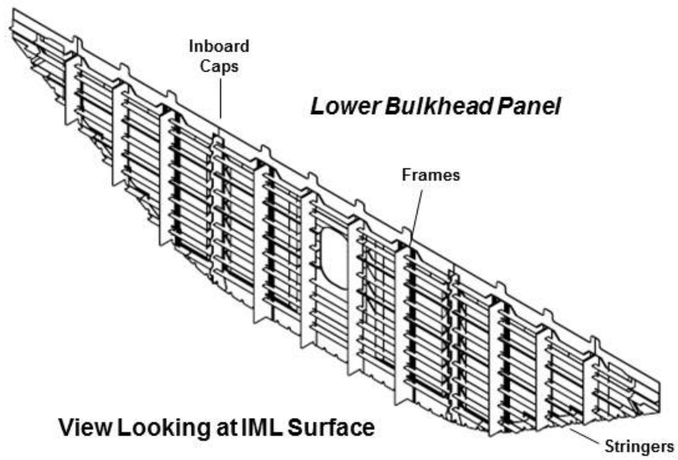


Figure 7. Lower Bulkhead Panel Design

1.1 Panel Edge Trimming

Both of the Lower Bulkhead panels were provided to this task in the cured condition (Figure 8), leaving only the edge trim operations to complete the panels before they could be delivered to the box assembly site in Long Beach, CA.

Figure 8. Cured Lower Bulkhead Panels Provided by Contract NNL13AA11C

Once the panel inspection and rough trim processes were completed at the Huntington Beach Stitching Center, the panels were loaded onto transportation dollies (Figure 9) and delivered to a local machining vendor where the net-trim machining operations would be completed.

Figure 9. Cured Panels were Shipped to Vendor for Edge Trim

The actual edge trim operations were relatively straight forward for the integral panel construction. The most important step was properly aligning the panel onto the machine bed at the outset, because the clamped-down position ultimately determines the relative location of the individual panel in the global coordinate system of the box geometry. This occurs because the determinant assembly holes are drilled into the panels at this stage and will later be used to pin the panels together with only minimal opportunities for further adjustment beyond that point. Consequently, the panels were carefully measured and rigged before the start-of-machining was approved by a Boeing manufacturing engineer. The white tape markers in the photo below (Figure 10) show the frame end-position measurements made prior to confirming the final rigged position of the panel.

Figure 10. Panels were Carefully Rigged onto the Machining Bed Prior to Machining

Once the panels were properly positioned, the edges were restrained and sandbags were placed in the center regions of the panels to dampen panel vibration and reduce cutter chatter during machining. (Figure 11)

Figure 11. In-progress Machining of a Lower Bulkhead Panel

Some of the primary edge trim operations are shown here in Figure 12. The general approach was similar for all of the panels, where an inch of material is removed from the perimeter, stringer pass-through features are cut, stiffener runouts are profiled at the ends, and a scalloped pattern is created along the top of the integral cap members.

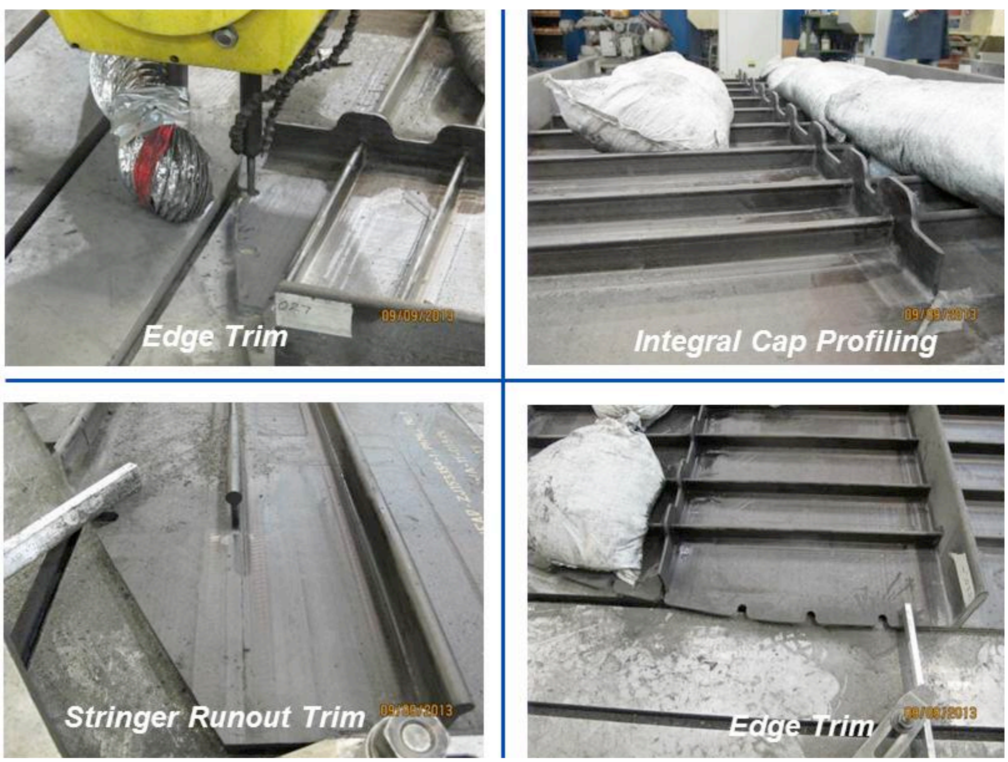


Figure 12. Common Edge Trim Operations

Once the machining and inspection operations were completed, the panels were delivered to the Long Beach, CA assembly site and positioned onto the assembly fixture. Positioning of the first Lower Bulkhead Panel is shown below in Figure 13. Both of the bulkhead panels were completed in this manner, and then were placed onto the assembly jig and located using the determinant assembly (DA) holes that were drilled by the vendor. This approach worked as planned and required no further adjustment or bumping of the panels to achieve a better fit condition. By inspecting the DA hole alignment between the panels, the good coincidence of the holes validated that the DA approach and net-molding design features designed into the panels had worked well.

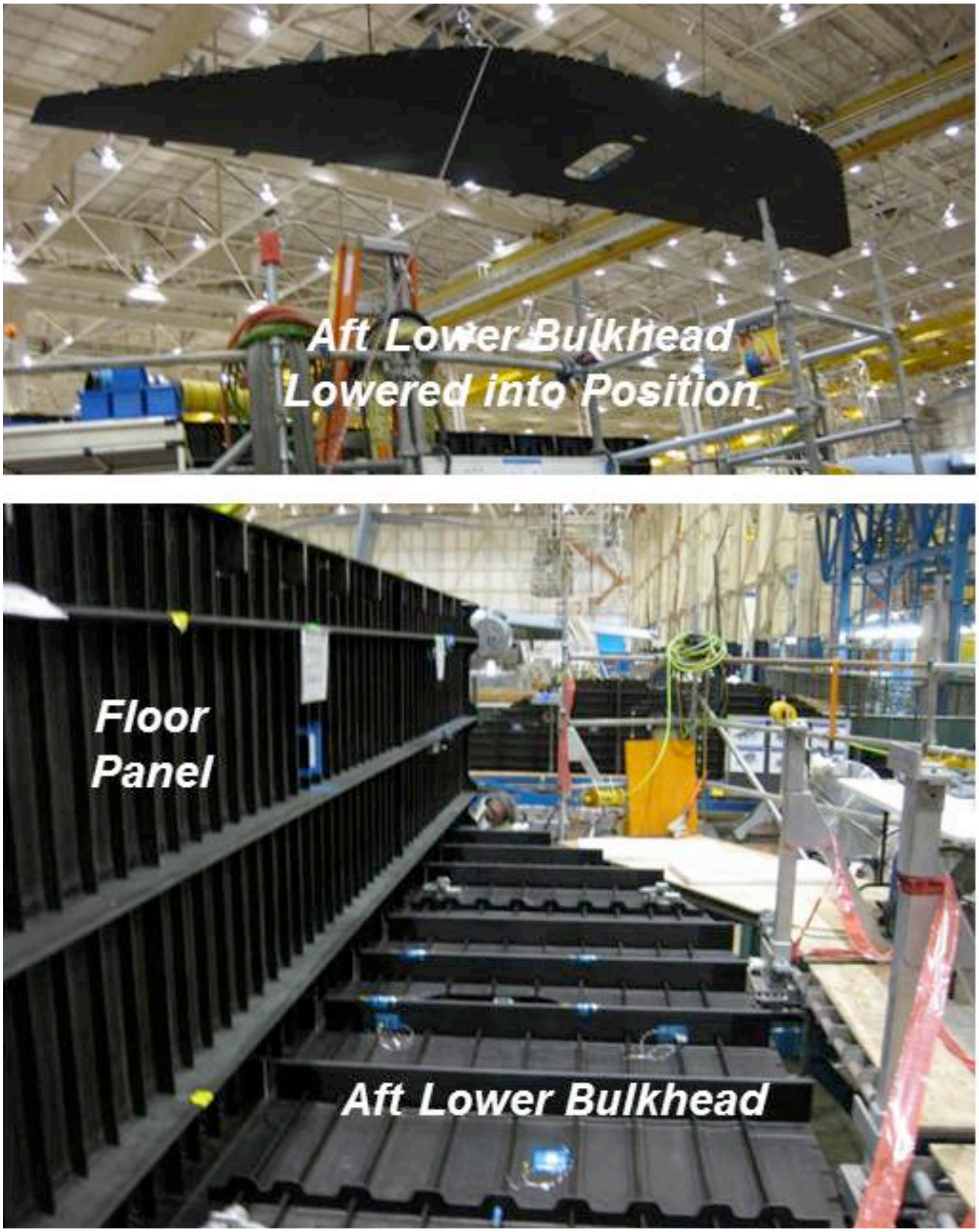


Figure 13. Completed Panels Delivered to Long Beach Box Assembly Site

2.0 Side Keel Panel (Left and Right)

The Side Keel Panel Assembly is comprised of 19 stringers, three frames, and four integral cap features that support the lower center and outboard rib panels (Figure 14). While the majority of the panel is flat, one edge has a 90-inch radius of curvature that forms the lower curved portion of the box assembly. Although these were the only non-flat panels used in the box assembly, the basic stiffener features remained nearly identical to those used in the flat panels by maintaining perpendicularity to the outer moldline (OML) surface along the curved region. This slight difference, as well as the addition of curvature to the panel, had minimal effect on the panel design and manufacturing operations. All of the panel edges were built up to accommodate the mechanical attachments and metallic fittings that are used along the edges and corners to create the pressure-tight box assembly.

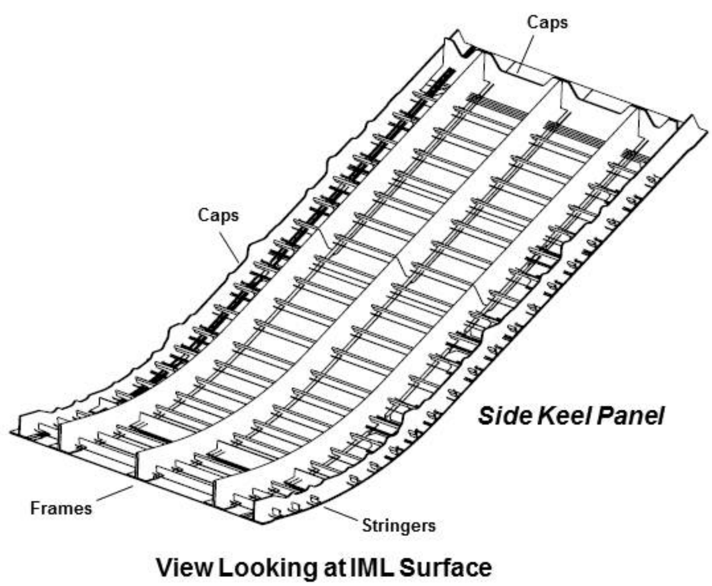


Figure 14. Side Keel Panel Design

Although the panel detail parts were prepared on a prior task order, the tool set-up along with the majority of the panel fabrication tasks were completed under this task order – as such, only those activities will be described in the following sections.

2.1 Tool Preparation

As the stitching tool was being assembled, it quickly became apparent that the tool design discrepancies encountered in the foam blocks on the other panels would continue to plague the program. The root cause of this problem was an incorrect interpretation of the dry preform bulk geometry as compared to the as-cured and modeled engineering net-part dimensions. The inconsistent application of the predetermined tool design parameters by the tool designer engineers made it clear that a better design process would be needed to eliminate the problem of accurately modeling the cutter path for the foam block machining operations. As the foam blocks were assembled, the lack of symmetry across the stitch tool surfaces indicated that model errors were present, and that the foam block models would require further interrogation to discern where the problems had occurred. A typical example of what was encountered during the set-up task is shown in Figure 15. In this example, the step heights needed to accommodate the skin

stack drop-offs were incorrectly modeled and further rework would be required before the tool could be used to assemble and stitch the preform.

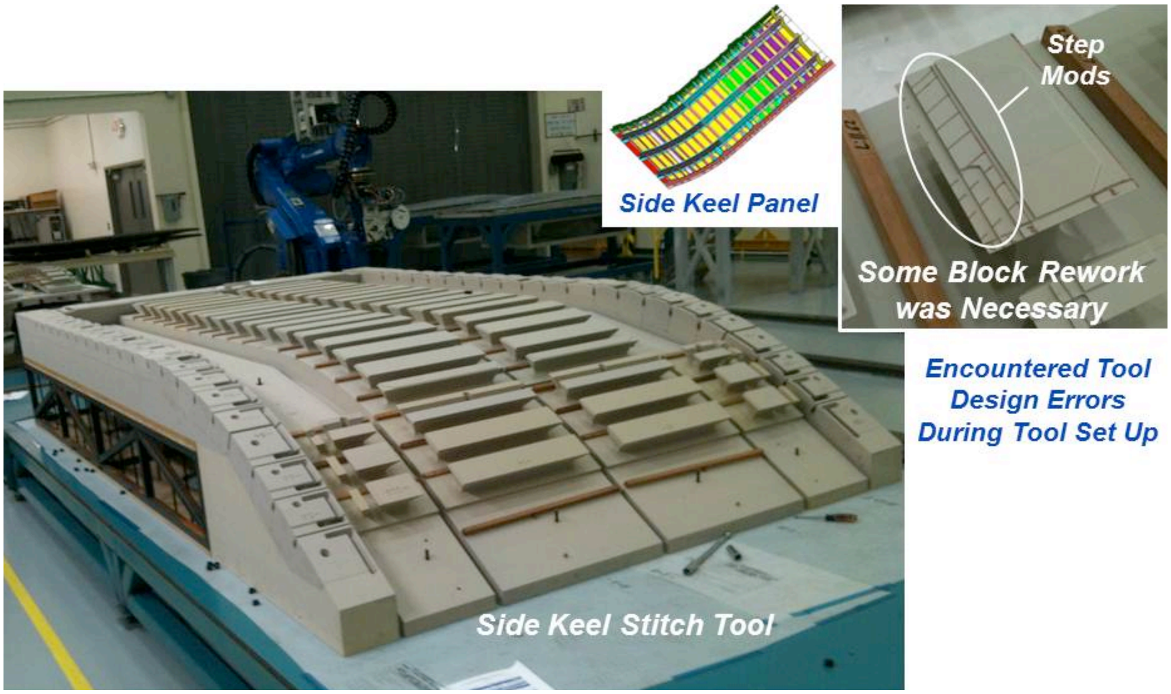


Figure 15. Stitch Tool Modifications

Local rework of the foam blocks was common and had a substantial impact on the overall panel fabrication schedule. The unplanned events required to reengineer the computer models and modify the blocks added many weeks to the panel fabrication timespans. The use of a single common stitch tool table to locate the blocks onto also exacerbated the situation, because it precluded the option of simultaneously reworking multiple panel block sets since only one table was available to rig the blocks and that table was always needed in the stitching cell. Although the tooling commonality scheme reduced the upfront acquisition costs, it also limited the options for discovering tool design errors and ultimately reworking those errors in a timelier manner.

Once the blocks were corrected, the curved portions of the tool presented no undue problems, and there were no further issues with its use. The general approach for accommodating the curved sections of the panel onto the base of the stitching tool is pictured in Figure 15. A steel truss table was used to raise the flat portion of the panel high enough for the curved blocks to rest on the base table. The taller working surface and panel curvature were easily incorporated into the numerically-controlled path of the stitching head. Once the blocks were corrected, this approach worked well and achieved the original design intent of minimizing the overall tooling costs required to achieve curved panel fabrication.

A similar approach was used for the cure tool except that since the OML is the controlled surface, the extension portion of the tool ramps upward from the flat surface of the cure tool. The curved ramp extension was a hollow welded box structure that was sealed against the surface of the cure tool; resulting in a modified lofted tool surface that also maintained vacuum integrity. The primary challenges of using such an approach to reduce tooling costs was, 1) sealing the edges, 2) creating a smooth transition at the edge of the ramp so the skins would not be stepped or joggled there, and 3) ensuring that resin could track the full height of the ramp. To validate

that these conditions could be met, a single-stack infusion trail was run (Figure 16). The results of this trial validated the tooling approach, as everything worked as planned.

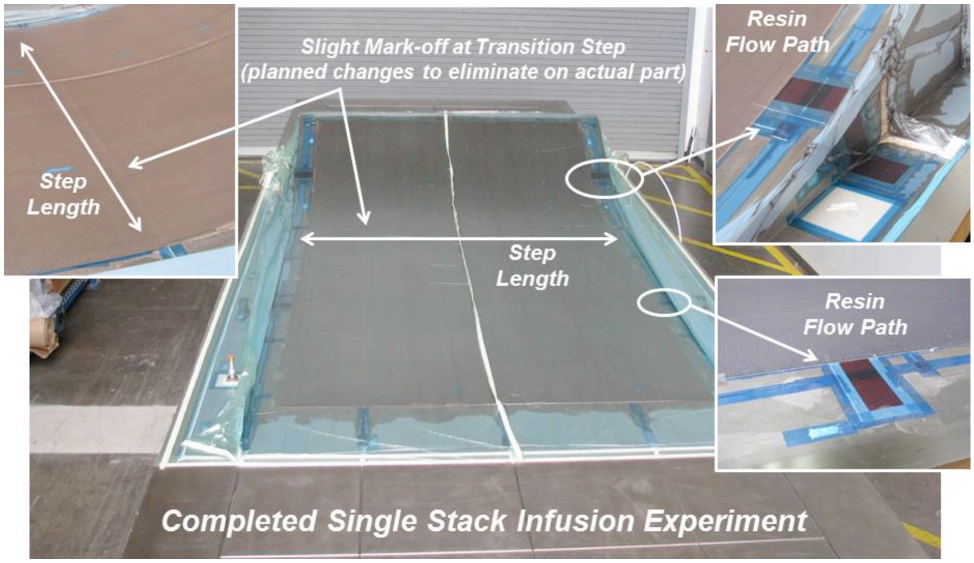


Figure 16. Cure Tool Checkout and Infusion Demonstration

2.2 Preform Assembly

The primary challenge of building the Side Keel Panel frames was in draping the fabric stacks across the curved segments. The initial part design called for a continuous layer of Class 72 material to be draped from end-to-end. When this was actually done, excessive material buckles occurred along the interior frame cap bend line. After several trials, it was determined that shorter material lengths would be required to eliminate the buckling or bunching condition that occurred in the thicker triaxial fabrics. The number of extra splices and their locations were generally dictated by where the wrinkles occurred in the original longer stacks. Additional $\pm$45-degree stacks were also added to bridge the new butt splices and maintain load continuity. These new thicker frame lay-ups were then updated in the drawings and stress report. (Figure 17)

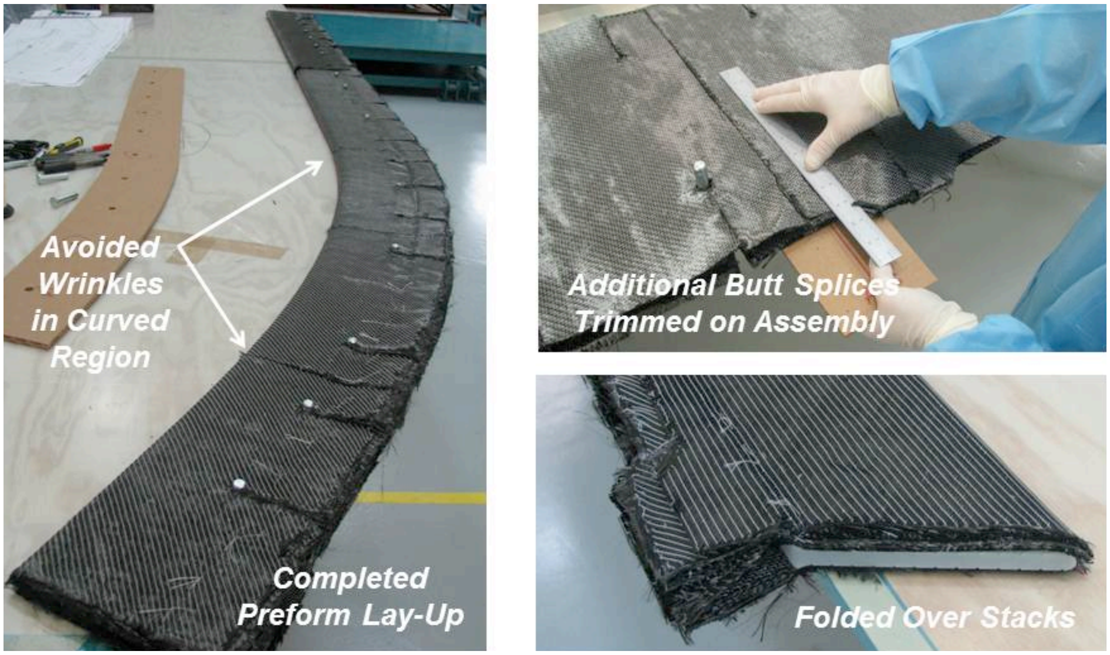
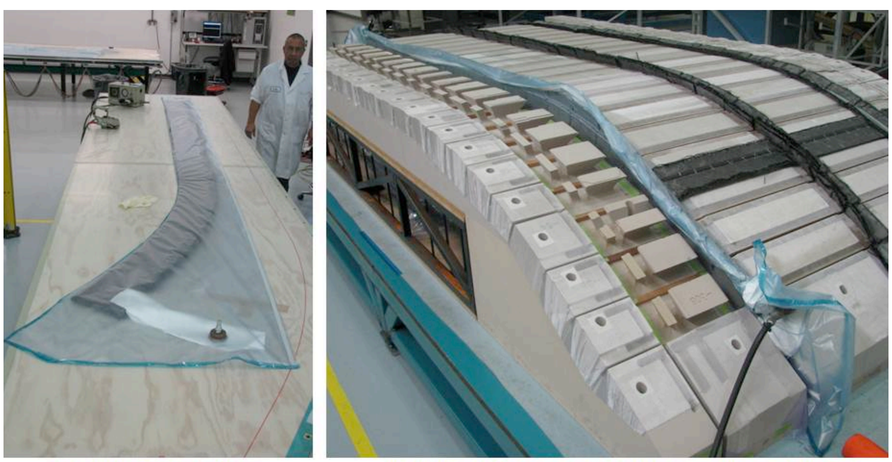


Figure 17. Curved Frames Required Additional Splices to Avoid Fabric Wrinkles

To avoid making changes to the foam blocks for the thicker frames, a new step was introduced into the preform assembly process. The thicker frame preforms were vacuum bagged to compress the bulk fabric thickness and then inserted into the existing stitch tool slots (Figure 18). Although the fit-up was a little tighter than normal, the vacuum bag was easily removed, and no modifications were necessary for the foam blocks to accommodate the new thicker frames.



Vacuum Bag Used to Compact Frame Preform

Additional Stacks Added to Frame Assembly Fit Without Modifying Stitch Tool Gap

Figure 18. Revised Frame Lay-ups Placed in Existing Stitch Tool

Once the frames and integral cap details were positioned inside the tool, the stringers were inserted, the rods were pulled through, the tear straps, doublers, and skin stacks were laid down, so the single-sided stitching sequence could begin. (Figure 19)

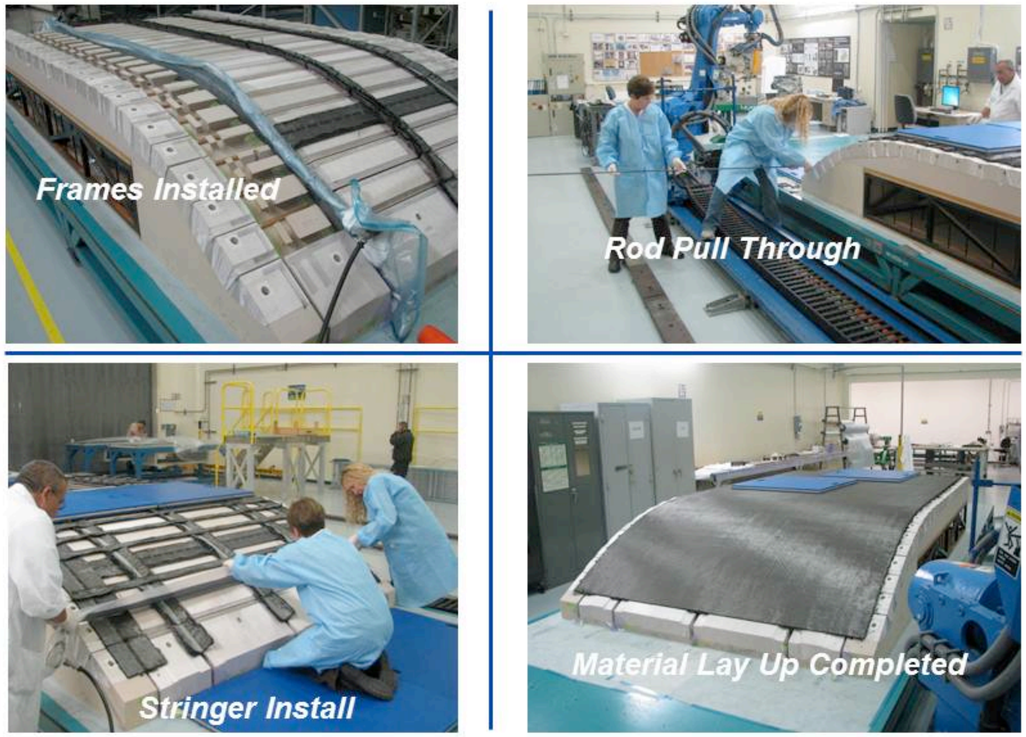


Figure 19. Keel Panel Preform Build Up

The single-sided stitching operation (Figure 20) is a multi-needle robotic stitching system where a three-dimensional seam is inserted in the preform to attach the frame and stringer flanges to the skin. The needles penetrate the preform and enter grooves in the tool that are placed at the stitching seam locations to provide clearance for the sewing needles as they exit from the backside surface of the preform. This unique aspect of the approach, whereby access is only required from the OML of the part, enables tooling configurations that are necessary to support the complex internal geometries of the dry fabric preform for the bi-directionally stiffened structures being fabricated in this program.

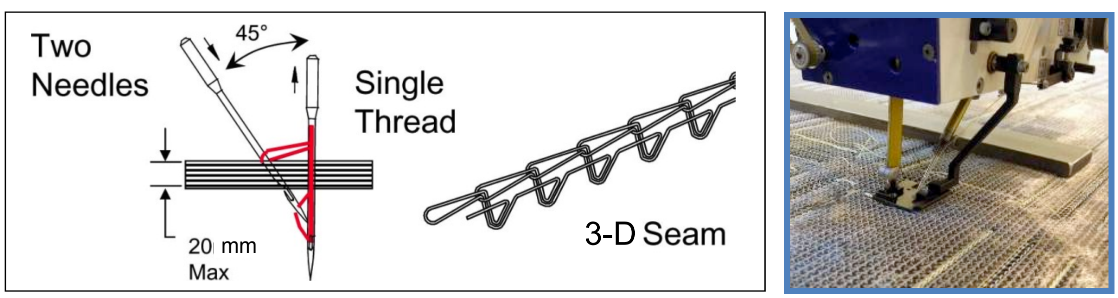


Figure 20. Single-Sided Stitching Technique

Once the preform details were positioned inside the stitch tool, the initial stitch seams were inserted along the stringers before the transverse stitching for the frame and integral cap members was filled in. Both the left and right-hand units for the Side Keel panels were completed in this manner (Figure 21) and then rotated (Figure 22) and lifted onto the cure tool. The bands securing the preform to the tool were released, and then the stitch tool details (steel table, foam blocks, and wooden frames) were removed from the preform, leaving only the self-supporting stitched preform on the cure tool surface.

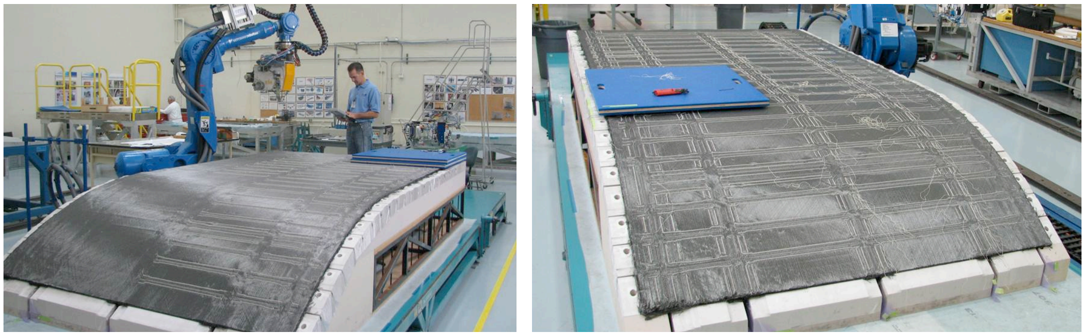


Figure 21. Side Keel Panel Stitching Completed

Figure 22. Preform in Rotated Position Being Lifted onto Cure Tool

2.3 Cure Tool Assembly and Part Cure

Prior to transferring the preform to the cure tool table, the inner moldline (IML) tooling details and curved ramp weldment was cleaned and readied for installation onto the cure tool table (Figure 23). Although the preform is designed as a self-supporting structure, these under-bag tooling elements play a critical role in definitively molding the mating surfaces used to join the adjacent panel assemblies. These tooling plates mold one side of the integral cap feature, locate frame stations and position stringer rod ends. In addition to the steel tooling, silicone mandrel bagging aides were also used to fill the sharp corners and simplify the bag pleating operations.

Figure 23. IML Tool Details Cleaned and Ready for Assembly onto Cure Tool

Once the preform was positioned onto the cure tool, the internal tools were added – a partially completed cure tool build up is shown in Figure 24.

Figure 24. IML Tools Installation Access Provided By a Deck Placed Over the Preform

Beyond the hard-tooled features molded by the steel plates, a number of soft-tooled features such as silicone rubber bagging aids on the stringers, latex rubber sheets on the frames, and peel-ply fabric on the IML surfaces, were also added before applying the vacuum bag (Figure 25). Such features are an important part of the overall resin flow network, as is the system of flow media that was added to the tool surface to provide flow paths that will allocate resin throughout the tool and preform.

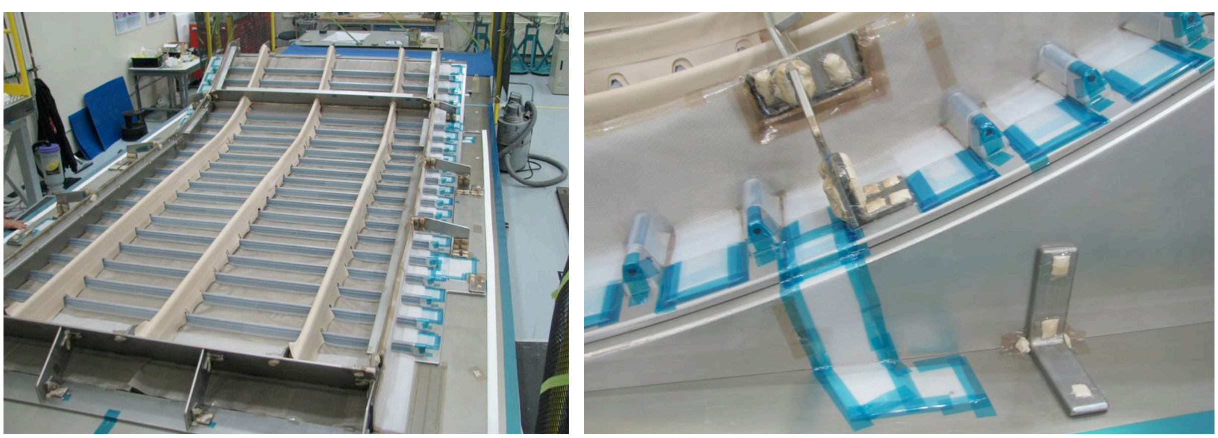


Figure 25. IML Tools and Bagging Details Create a Resin Flow Network

Creating such a system was complicated somewhat by the part curvature, which dictated the use of the ramp weldment in conjunction with the existing flat cure table. Normally, a dedicated cure tool with curvature and integrated resin flow channels would be used. As such, the network of flow media and taped connections seen in the photos was excessive as compared to the other panels that came off dedicated tools. The panel curvature also made the vacuum bag application

and pleating more difficult, as the technicians encountered some awkward positions reaching up the curved sections to make the final bag adjustments. (Figure 26)

Figure 26. Bagging Curved Part was Slightly More Difficult

After the double-bag system passed the leak checks, the tool was moved into the oven (Figure 27) and the part was infused and cured without any problems.

Figure 27. Moving Side Keel Panel Assembly Tooling into Oven

After the initial 250ºF cure, the part was removed from the oven (Figure 28) and debagged. All of the bagging materials and tooling elements are removed and the part then undergoes a 350ºF free-standing post-cure cycle that produces the final full-strength properties of the resin system.

Figure 28. Cured Side Keel Panel Assembly on Cure Tool

The cured panel assembly (Figure 29) was then inspected to document any deviations from the drawing and/or processing requirements. Once that was completed, the panels were released for edge machining at a local vendor. Both the left and right-hand Side Keel panels were completed in this manner.

Figure 29. Cured Side Keel Panel Assembly

2.4 Panel Edge Trim

The edge trim operation for all of the panels is generally the same as was described for the Lower Bulkhead Panel described in Section 1.1 of this report. The only real difference presented by the Side Keel Panel was the curvature, which required that an additional support table be constructed to support the panel when the panel was clamped down to the machining bed. This temporary tooling aid (pink foam structure in Figure 30) was created by the vendor using loft data provided prior to receiving the panels.

Figure 30. Panel Edge Trim Set-up at Machining Vendor

The machining operations went as planned without issue, except for one anomaly on the first unit - where it was discovered that two of the tabs on one of the integral caps were partially missing (Figure 31). This problem was eventually tracked back to a tooling change that was made when the cure tool was modified and those changes affected the preform edge trim dimensions. After realizing the error, the cure tool was further modified to move this particular design change onto the excess-trim area of the part and no further issues were encountered on the second unit.

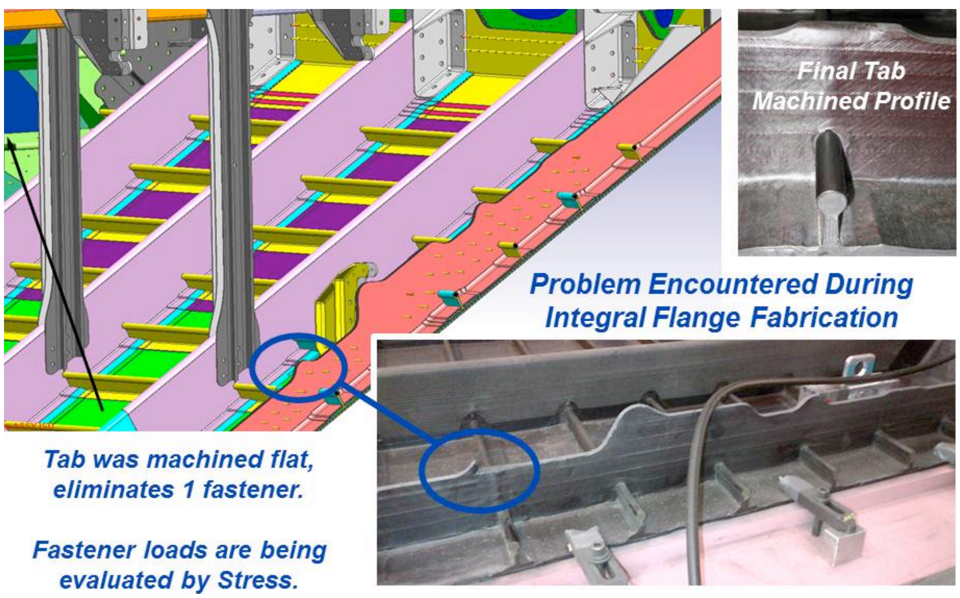


Figure 31. Missing Tab Condition at Two Locations

The fix for the first panel was to maintain as much of the remaining tab height as possible and machine it flat-and-parallel to the loft line (Figure 31). These instructions were communicated to the vendor and the panel machining was completed. The effect of this deviation was primary felt on the next-level assembly, where the missing tabs caused a short edge-distance for the fasteners. To avert this condition, two fastener positions were translated (as shown in Figure 32) away from the shorten tab edge - while also maintaining proper edge distance on the adjacent parts. The revised fastener locations were analyzed and all of the margins remained positive.

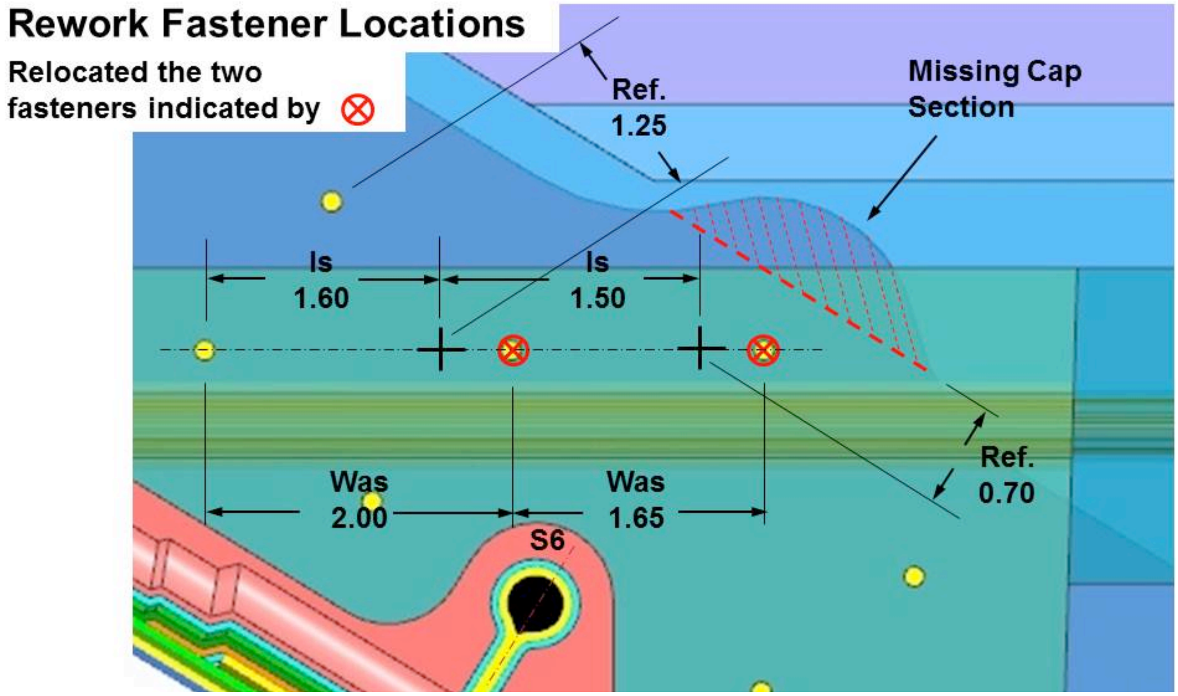


Figure 32. Moved Two Fasteners to Accommodate Mis-trimmed Tab

Once the tool and preform modifications were completed, the second unit was infused-and-cured, delivered to vendor for edge trimming, and then returned to the assembly site. (Figure 33)

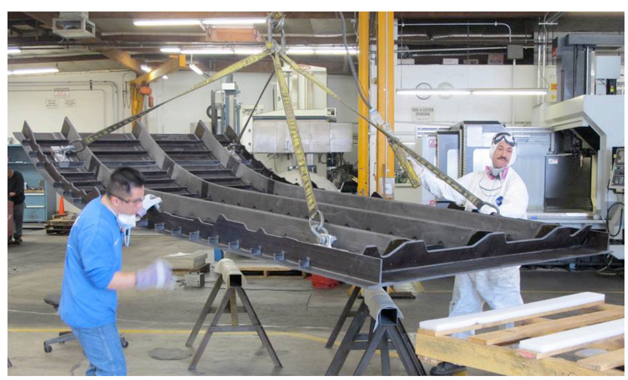


Figure 33. Second Side Keel Panel Shipped to Vendor for Edge Trim and Returned

3.0 Center Keel Panel

The Center Keel Panel Assembly is comprised of 11 stringers, three frames, and two integral cap features that support the forward and aft bulkhead panels. (Figure 34) The central region of the panel is the minimum 0.052-inch skin gauge which increases at the forward and aft edges and along the splices to the Side Keel Panel to accommodate the mechanical attachments and metallic fittings that are used to join panels and create the pressure-tight box assembly.

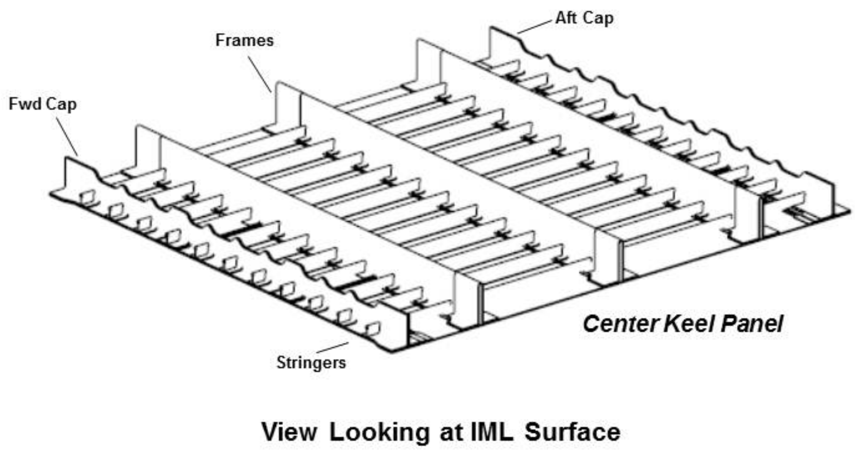


Figure 34. Center Keel Panel Design

3.1 Tool Preparation

Since the Center Keel Panel was the last of eleven PRSEUS panels that would be fabricated for the box assembly, the set up and checkout time for the last toolset went relatively quickly. All of the changes discovered on the previous panel block sets had been rolled through this set, and the tool designer engineers had rechecked the tool models several times (Figure 35).

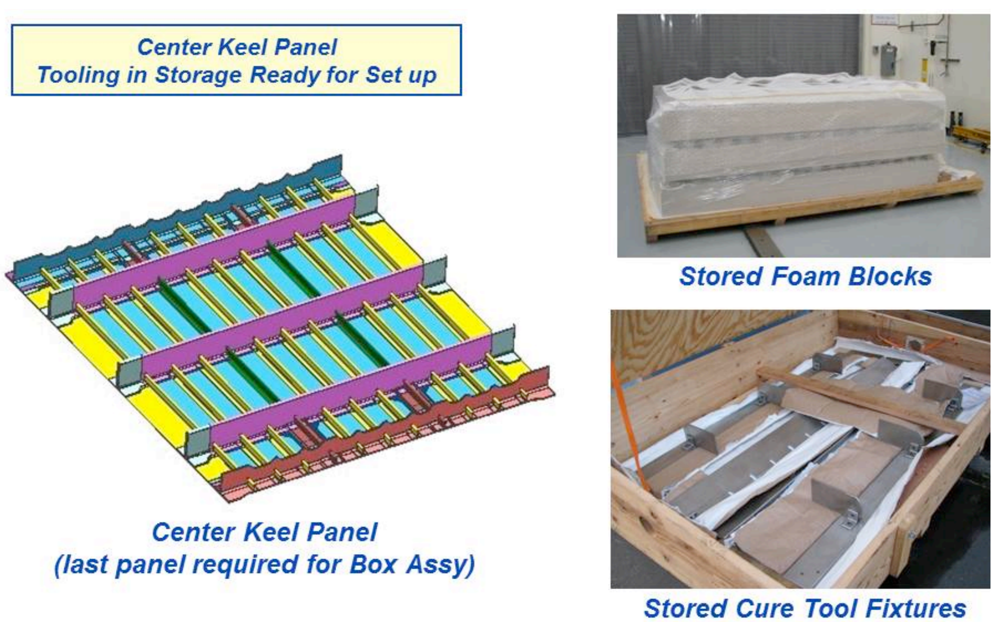


Figure 35. Center Keel Panel Stitch and Cure Tool Preparation

3.2 Preform Assembly

The relative smaller size of the panel simplified the preform build up so that the substructure details could be loaded within a few hours (Figure 36). As usual, the longest part of the preform assembly time was the tack-stitching of the stringer and integral cap fillets, which added several hours to the overall preform assembly timespan.

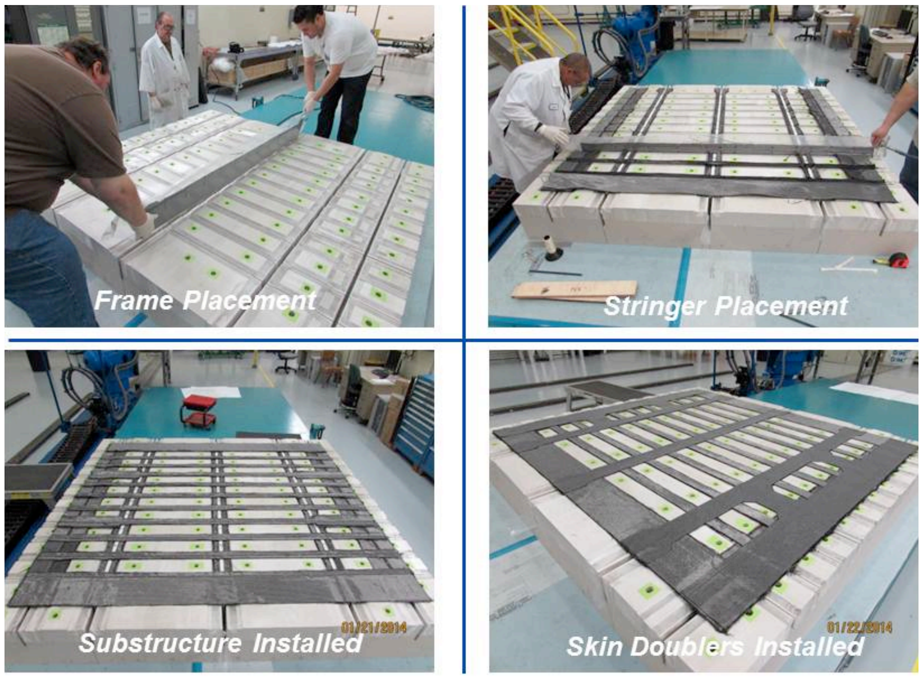


Figure 36. Center Keel Preform Assembly

Once the single-stack skins were positioned to complete the material placement, the stitching operation was started and completed in about two working shifts (Figure 37). Such a speed reduction is typical of the first-run through the stitch seam computer programs to minimize the chance of stitching head collisions with the preform and/or needle damage to foam core tooling. Once the accuracy of the programming and stitch seam location is demonstrated, then the run speeds could be substantially increased to cut down the overall stitching timespan.

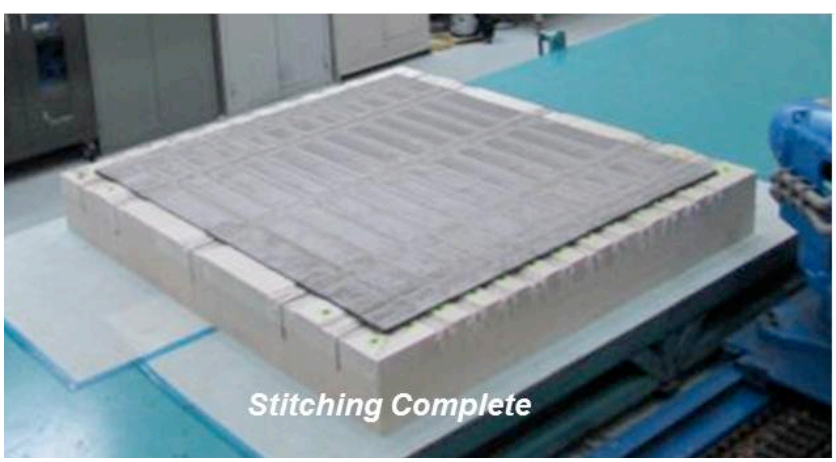


Figure 37. Center Keel Panel Preform Stitching Completed

3.3 Cure Tool Assembly and Part Cure

The completed preform was then transferred to the waiting cure tool (Figure 38) and bagged before being moved into the oven for resin infusion and curing. After curing and cool down, the panel was removed from the oven (Figure 39), debagged, and then post-cured. After the post-cure cycle, the panel was inspected and no anomalies were found (Figure 40 and Figure 41).

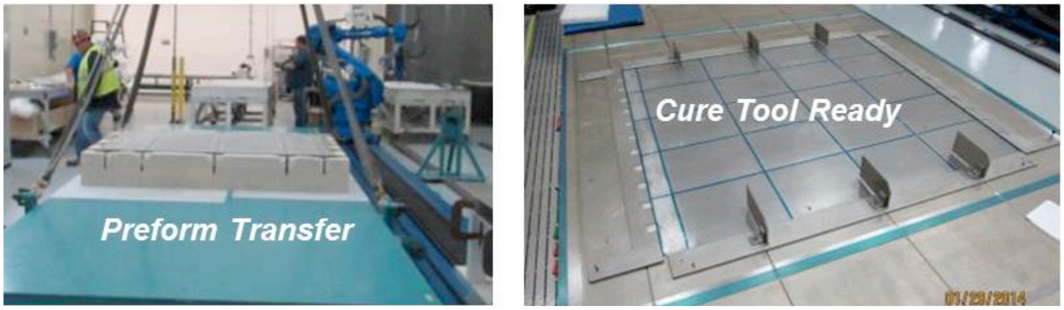


Figure 38. Stitched Preform Transferred to Waiting Cure Tool

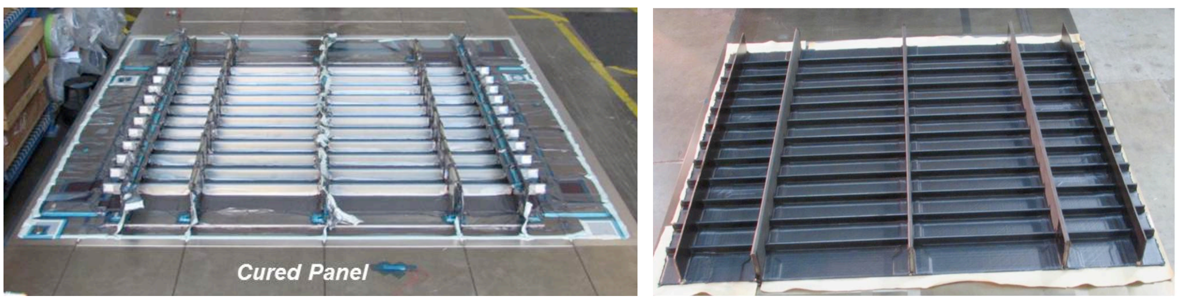


Figure 39. Cured Center Keel Panel - Bagged and Unbagged

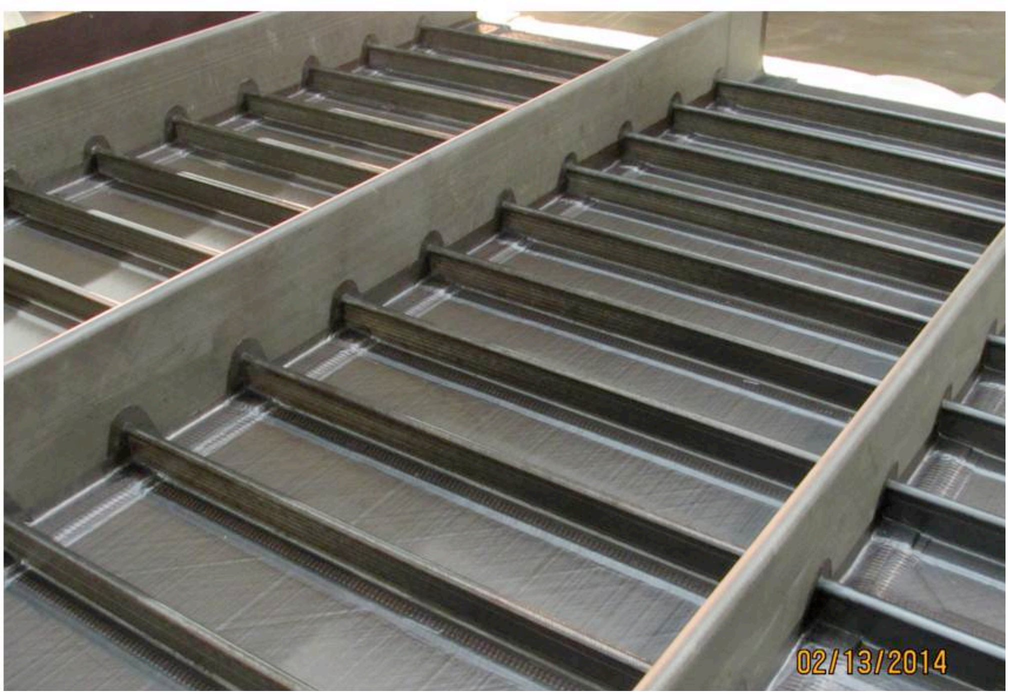


Figure 40. Cured Center Keel Panel IML Surface

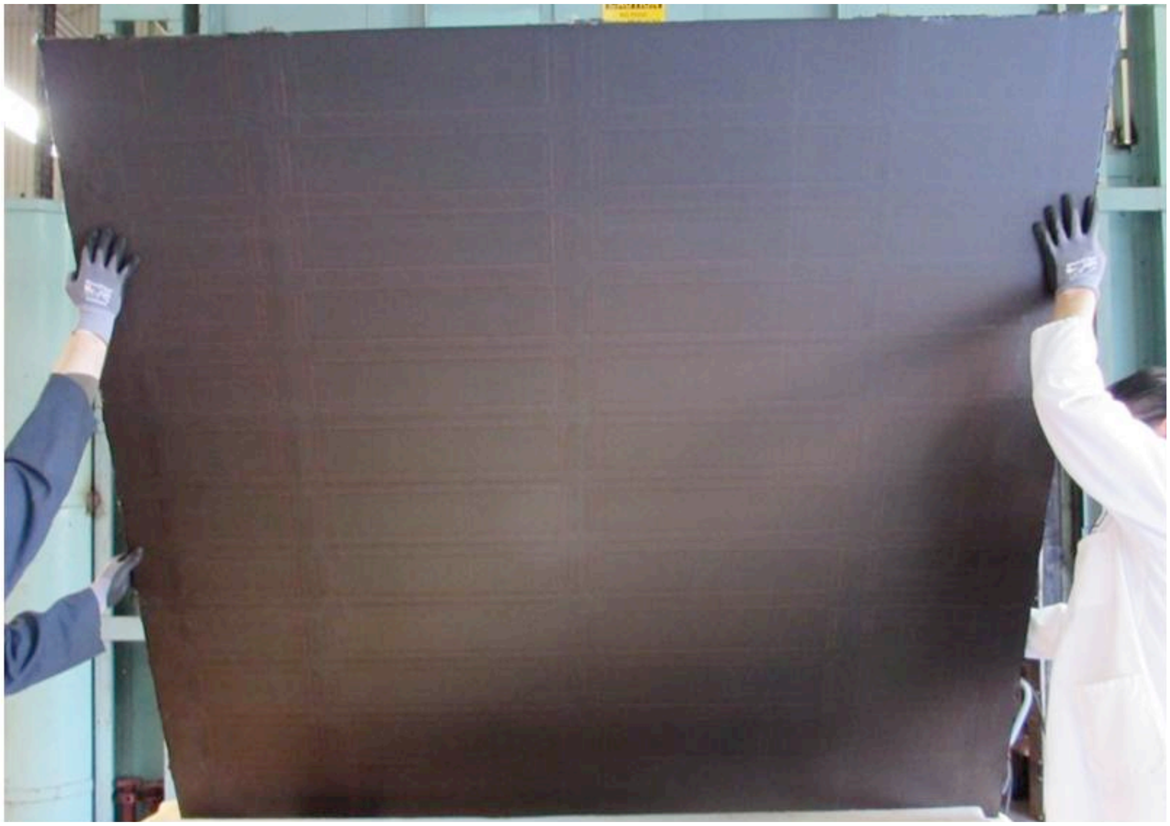


Figure 41. Cured Center Keel Panel OML Surface

3.4 Panel Edge Trim

The infused panel was delivered to the machining vendor for edge trim and then after completion of those operations returned to the Long Beach, CA box assembly site (Figure 42).

Figure 42. Center Keel Panel Delivered to Vendor for Edge Trim

The Center Keel Panel Assembly was the final hardware deliverable for the MBB for this task order contract (NNL13AB38T). The collection of lower section panels was then transferred over to the NNL11AA68T Task Order contract where they were assembled onto the upper section panels (Figure 43) to complete the MBB Test Article (Figure 44).

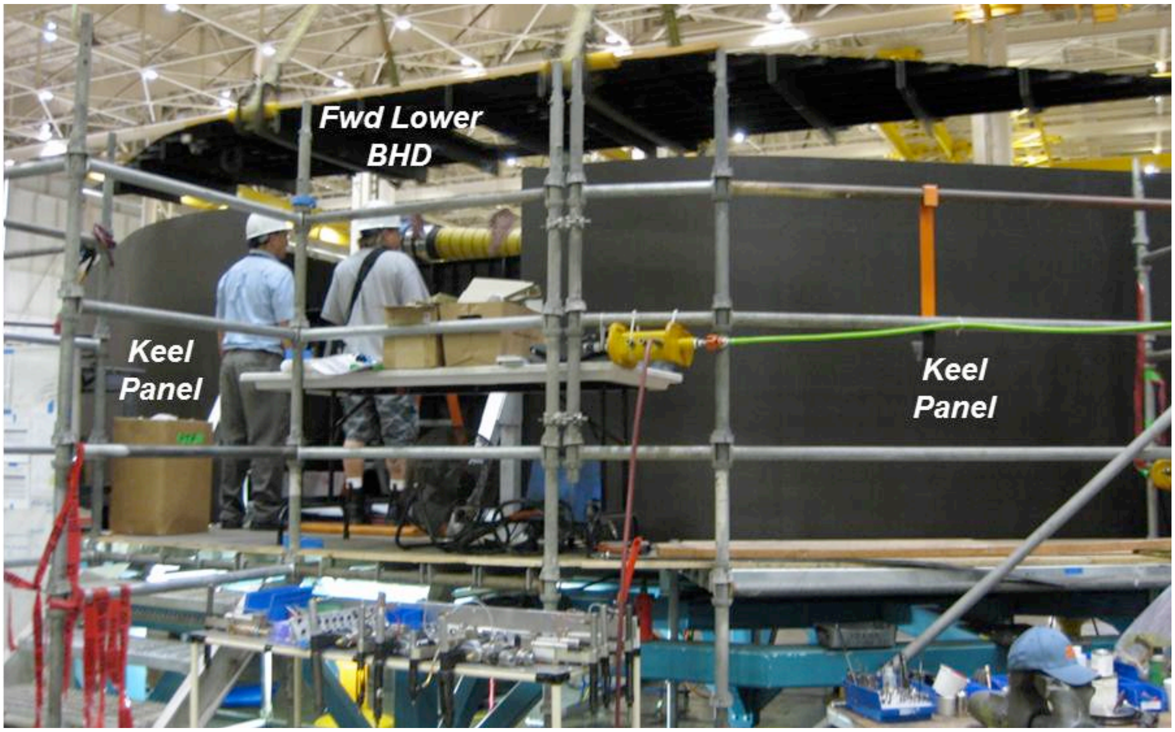
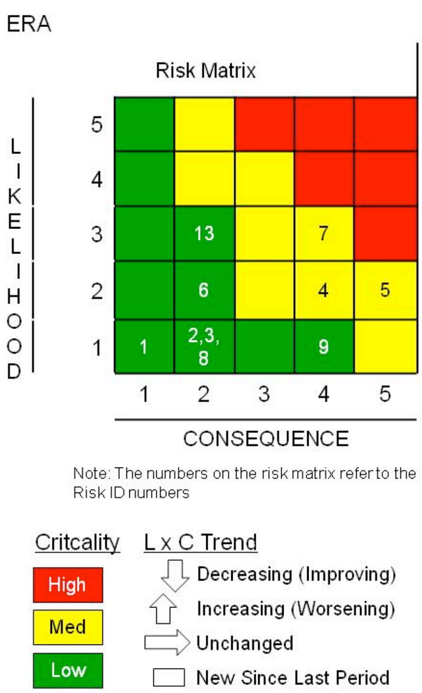


Figure 43. Lower Section Panels Lowered into Position at Box Assembly Site

Figure 44. All Panels Delivered (Center Keel Panel on floor in background)

4.0 Risk Mitigation for Panel Fabrication

As described in the introduction, most of the panel fabrication work for the MBB was done prior to Task Order NNL13AB38T (Figure 1). The prior work included risk mitigation and documentation. A Risk Assessment and Mitigation Plan (RAMP) for Task Order NNL11AA68T included descriptions of risks related to panel fabrication as well as test article assembly. The RAMP lists mitigations associated with each risk, and indicates the implementation status for each mitigation. The top risks for panel fabrication were for cure tool rework, stitching tool rework, infusion failure, availability of key personnel, and equipment failure and repair. The other risks in the RAMP were for test article assembly. A RAMP for Task Order NNL13AB38T was created when the task order began, in May 2013. The top ten risks for the overall MBB test article effort at that time are shown in Figure 45.



Rank	Trend	Risk ID	Approach (MWAR)	Title
1	⇩	7	M	Extra Shimming and Rework
2	⇨	5	M/A	Availability of Key Personnel
3	⇨	4	M/A	Equipment Failure and Repair
4	⇩	13	M	Dimensional Accuracy of Panels
5	⇨	9	M/A	Part Damage
6	⇩	6	M	Assembly Tool Rework
7	⇩	3	M/A	Infusion Failure
8	⇩	2	M	Cure Tool Rework
9	⇩	8	M	Material Shortages
10	⇩	1	M	Stitching Tool Rework

Figure 45. Top 10 Risks from May 2013

By the time Task Order NNL13AB38T began, mitigation efforts had reduced the risks for tooling rework and infusion failure, so that the risks of 'Availability of Key Personnel' and 'Equipment Failure and Repair' were the top panel fabrication risks. Two risks, 'Transfer of Large Preform to Cure Tool' and 'Building Largest-Ever PRSEUS Panels' had been closed. In Figure 45, the risks for extra shimming and rework, dimensional accuracy of panels, part damage, assembly tool rework, and material shortages, were primarily for test article assembly and not panel fabrication. The panel fabrication risks were stitching tool rework, cure tool rework, infusion failure, equipment failure and repair, and availability of key personnel. For the panel fabrication risks, a number of mitigations had been identified and carried out before Task Order NNL13AB38T began.

Mitigations for the risk of stitching tool rework included checking the fit of the stitching tool against the cure tool, double-checking the foam stitching blocks and wooden frames using computer models, reworking the blocks and frames before their use dates, and adjusting the

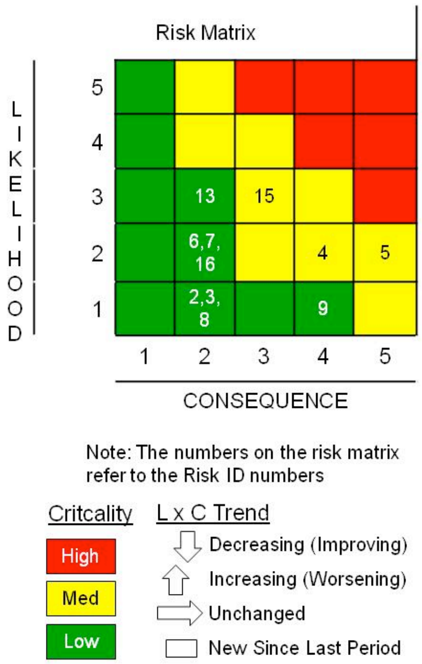
panel fabrication sequence to minimize movement of stitching tool elements and to accommodate the tooling rework schedule. For the risk of cure tool rework, the mitigations included check fitting the cure tooling details for each panel on the common cure table, checking the fit of the cure tool inside the oven, moving the controls for all valves to one side of the tool, and performing bench tests to optimize the infusion and cure parameters. To reduce the risk of infusion failure, process improvements such as double-bagging and the use of bagging aids were incorporated, and an improved vacuum bag handling process was implemented based on lessons learned with the crown and floor panels. For the risk of equipment failure and repair, mitigations included starting to use a new stitching head prior to fabrication of MBB panels, replacing and recalibrating heating elements, and refurbishing air conditioning equipment and resin infusion equipment regularly. To ensure the availability of key personnel, stringer and frame preforms were fabricated ahead of schedule to free up key people during panel fabrication, planned absences were coordinated with the critical path schedule, and training of additional personnel was initiated.

Risk mitigation activities continued under Task Order NNL13AB38T. They included more checks of the stitching tools using computer models, to ensure accuracy of the tooling before stitching began. As much as possible, reworking of the tools was done off the critical path of the stitching schedule.

To address schedule delays that could result if a vacuum bag was damaged and a replacement bag had to be ordered, multiple bags were procured prior to bagging each panel. This approach avoids the lead time for a replacement bag, and the cost for any unused bags is small compared to the benefit. Another concern involving lead times was for an infusion failure, or any other event that could result in a replacement panel having to be made. The labor cost for fabricating a replacement panel was too high to be included as a risk mitigation solution, but to protect against the lead times for obtaining materials for a replacement panel, some of which were several months, materials were ordered in advance. Foam blanks, resin, and warp knit fabric were all procured for this purpose.

Finally, as mentioned in Section 2.1, an infusion trial was performed with the cure tooling for the side keel panels, to verify that the extension tools to support the curved ramp would work properly. The trial was successful, and so were the infusions for both side keel panels.

By November 2013, the panel fabrication risks had been reduced over time, and were at the bottom of the risk table, or off the table entirely, as shown in Figure 46. The top panel fabrication risk was equipment failure and repair.



Rank	Trend	Risk ID	Approach (MWAR)	Title
1	⇨	5	M/A	Availability of Key Personnel
2	⇨	15	M	Assembly Schedule
3	⇨	4	M/A	Equipment Failure and Repair
4	⇨	9	M/A	Part Damage
5	⇨	6	M	Assembly Tool Rework
6	⇨	7	M	Extra Shimming and Rework
7	□	16	M/A	Impact of C-17 Program Ending
8	⇨	2	M	Cure Tool Rework
9	⇨	3	M/A	Infusion Failure
10	⇨	8	M	Material Shortages

Approach

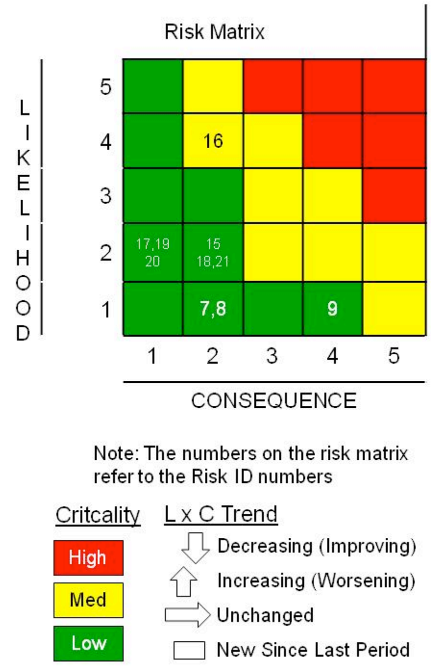
M – Mitigate W – Watch A - Accept R - Research

Figure 46. Top 10 Risks from November 2013

During panel fabrication under Task Order NNL13AB38T, some risks were realized, but the issues were resolved without any impact to the overall MBB test article effort. The risk of equipment failure and repair was realized more than once. In one case, the stitching robot experienced an electrical problem during fabrication of the first side keel. The robot was down for six days. Another equipment failure that interfered with the fabrication of the same panel involved the humidity control system in the fabrication lab. Preparation of the panel for infusion had to pause until the humidity got back within range for safe handling of the vacuum bag. Problems with seals in the resin infusion pumps were discovered just before infusing a panel, on a couple of occasions. In these cases, the practice of checking or refurbishing the equipment before use prevented an equipment failure during an infusion, when the consequences could have been severe.

As the only curved panel for the MBB test article, the first side keel experienced various delays as technical issues were worked out. One issue involved the draping of fabric over the curved sections of frames, for which a revised layup was needed. Difficulties in installing bagging aids in the curved region were another source of delay. Just when these issues were resolved, the risk of availability of key personnel was realized. To regain schedule, staffing increases were requested, and staff were not available. However, this situation was temporary, and a successful schedule recovery effort was eventually implemented. It involved added staff as well as overtime work and work on weekends.

When panel fabrication was completed in February 2014, the associated risks were closed. Figure 47 shows the risk table from that time, and it was populated fully with risks related to test article assembly.



Rank	Trend	Risk ID	Approach (MWAR)	Title
1	⇧	16	M/A	Impact of C-17 Program Ending
2	⇨	9	M/A	Part Damage
3	⇩	15	M	Assembly Schedule
4	▭	18	M/A	Availability of Key Assembly Support Personnel
5	▭	21	M/A	Re-Work for Shipping Fixture
6	⇩	7	M	Extra Shimming and Rework
7	⇨	8	M	Material Shortages
8	⇨	17	M	Availability of NASA's Super Guppy
9	▭	19	M	Delay in Readiness of Portable Milling Machine
10	▭	20	M	Procurement Delay for Shipping Fixture

Approach
M – Mitigate W – Watch A - Accept R - Research

Figure 47. Top 10 Risks from February 2014

The attention given to the panel fabrication risks, mitigation efforts, and prompt responses to issues, contributed to the successful completion of the panel fabrication effort. All of the panels for the MBB test article from Task Order NNL13AB38T were delivered without any impact to the test article assembly schedule.

5.0 Alternate Center Keel Panel

The Alternate Center Keel Panel (Figure 48) assembly consists of 11 stringers, three frames, and two bulkhead caps features all integral to the panel, like the original center keel panel. The main differences between the two panels is that two of the frames are the new solid-laminate designs without a foam core, six of the 11 stringers incorporate a new layup wrapping the rod, and four of the 11 stringers are coated with adhesive. The skin of the panel has the minimum 0.052-inch skin gauge orientated in the direction of the frames, and did not increase in thickness at the side edges (toward the ends of the frames) as in the original center keel. The integral caps of the alternate center keel panel have three zones, each with a different density of stitching rows in the cap web.

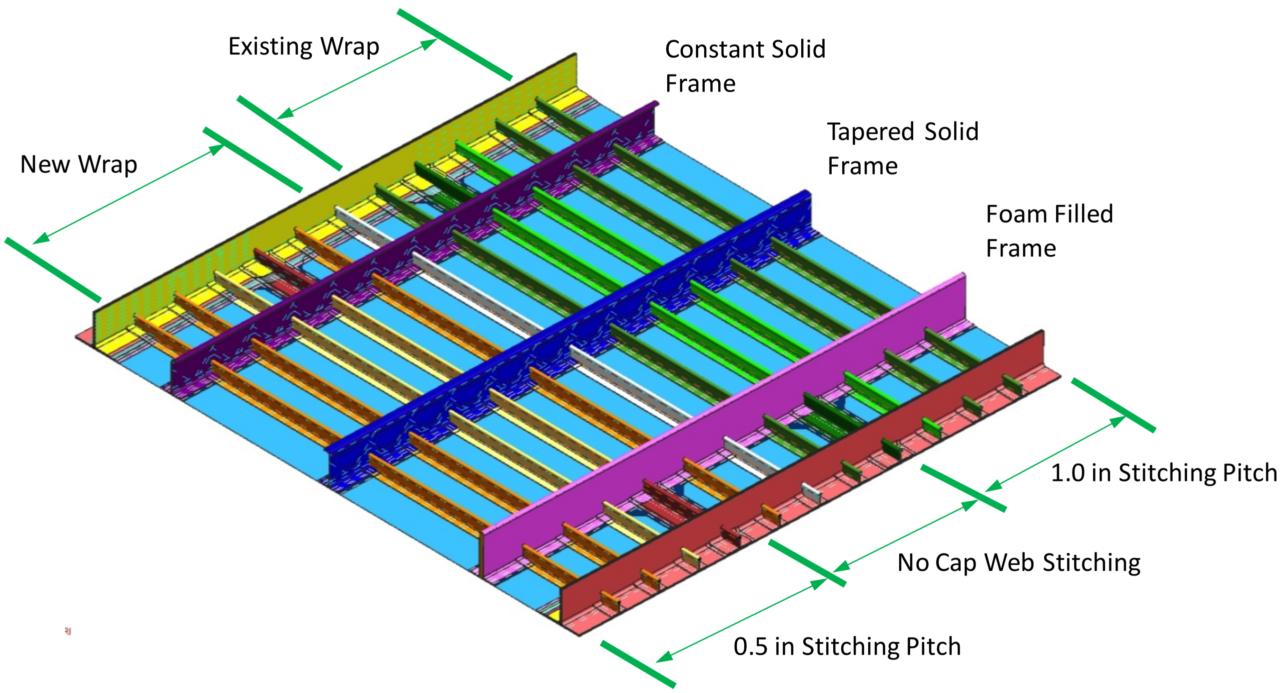


Figure 48. Alternate Center Keel Panel Design

In addition to its distinctive design features, the alternate center keel panel is distinguished from the original center keel by several manufacturing features. The stringer and frame dry-fiber preform details were stitched using a new two-sided stitching head and support jig. The solid-laminate frames were built for the first time in this panel, and employ new mold tool designs. One of the two solid frames uses a one-sided frame mold tool, and the other uses a two-sided mold tool. Between the invar cure table and the preform, the steel perforated plates used for previous panels were replaced with invar perforated plates.

The alternate center keel panel was a risk mitigation article. It would supply cured panel that detail section could be cut out and quickly bolted into place in case the MBB needed a quick repair involving a large section. If no such repair was needed, separate panel features could be tested.

Considering the number of new features in the alternate center keel panel, a risk reduction 'bench test' panel was included in the fabrication effort, to check out the design of the solid-laminate frames and their tooling before the actual panel was made. This 24 in. by 36 in. panel shown in

Figure 49 has six stringers and one frame. The bench test provided useful information which was incorporated into tool designs for the alternate center keel panel.

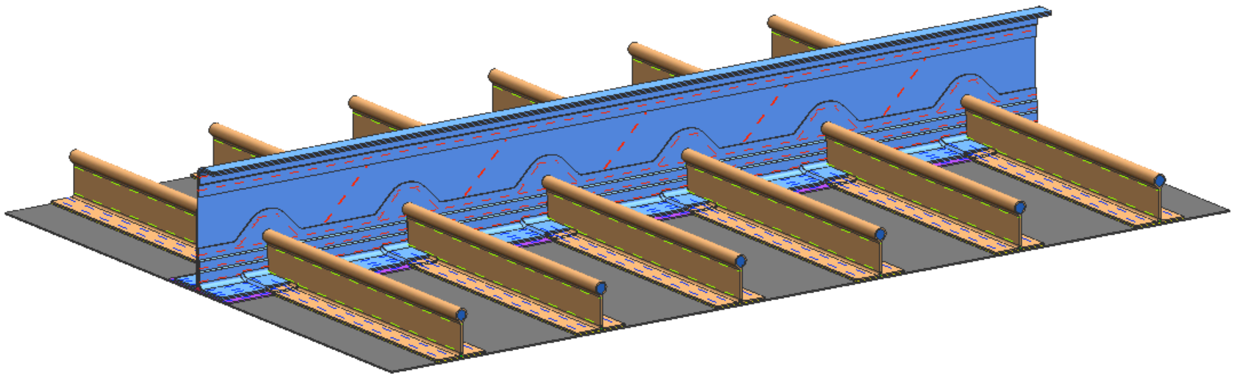


Figure 49. Solid Frame Risk Reduction Panel (ZJ153958)

A schedule for the design and fabrication of the alternate center keel panel is shown in Figure 50.

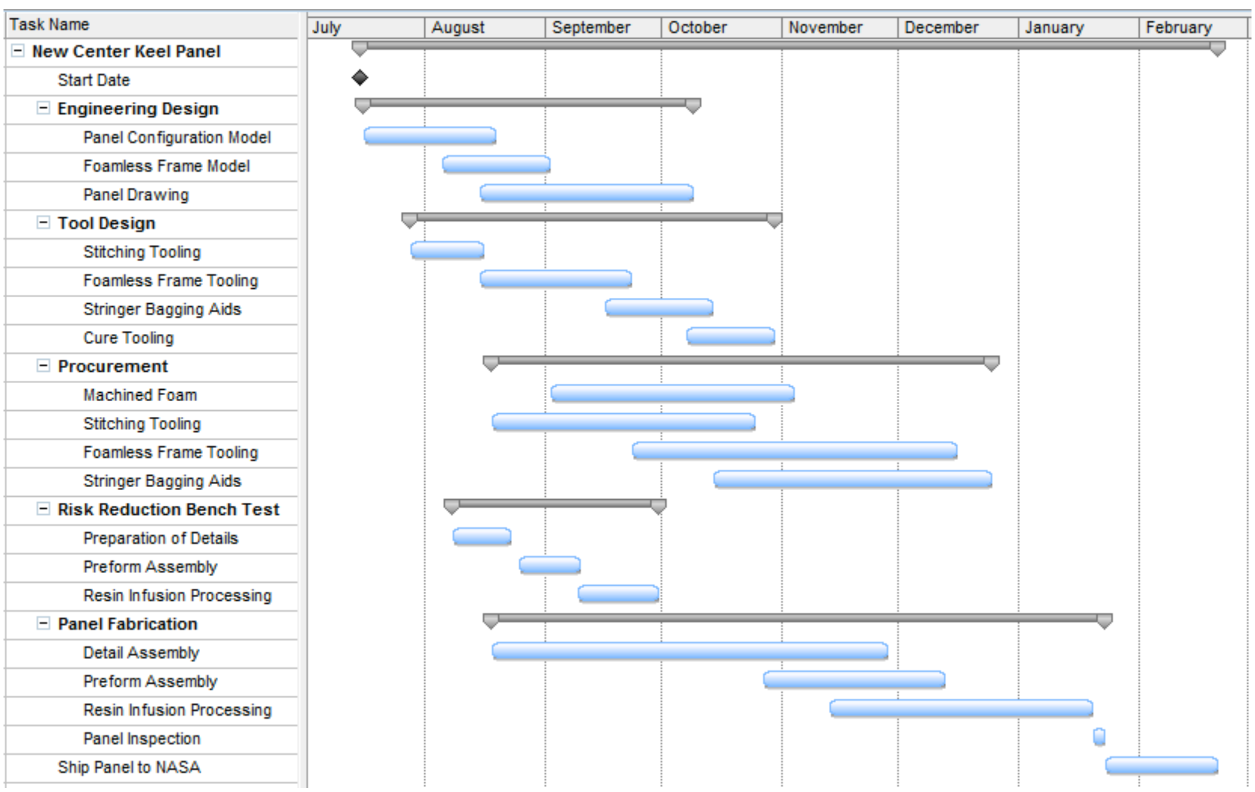


Figure 50. Schedule to Complete the Alternate Center Keel Panel

5.1 Design

The panel incorporated two solid frame designs and one foam filled frame, as shown in Figure 51. The original foam frame configuration was designed around the high compression loads that a Hybrid Wing Body (HWB) fuselage would generate.

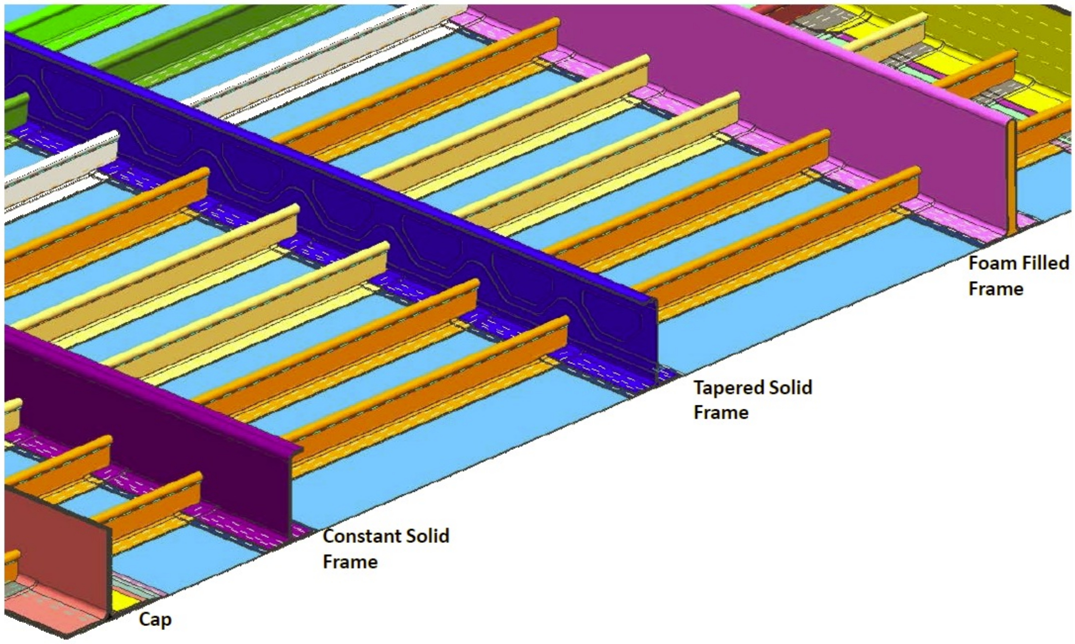


Figure 51. Three Separate Frame Configurations

The first solid frame is a constant-thickness frame that was also designed to primarily support high compression for the HWB fuselage. Although it is 21% lighter than the foam filled frame, the frame was not sized to HWB loads other than an equivalent compression load. Therefore, an actual weight difference is unknown. The solid frame cross section is a "J" section, shown in Figure 52. The frame is attached to the skin with flanges on both sides of the web with stitching through the frame flange, frame tear strap and skin. The symmetrical load path with two attaching flanges reduces the bending in the radius at the base compared to a "Z" or "C" cross section frame. The "Z" or "C" cross sections are normally used in bolted structure to reduce assembly time and the number of holes in the skin by eliminating one flange. But with stitching, the other flange is easily sown to the skin so a more efficient structure can be used without the increased cost of assembly. The addition of stitching in the frame web gives the solid frame damage-arrestment capabilities similar to the skin. Local stitching is added around each keyhole to reinforce the high stress areas in the frame webs and contain any damage to a small localized area in the event damage grew out from the keyhole. Diagonal stitching across the entire frame web divides the web up into six-inch segments, minimizing the progression of damage down the length of the frame web. Stitching was also added at the radius tangent lines to arrest damage propagating from the fillets to the frame flanges or web.

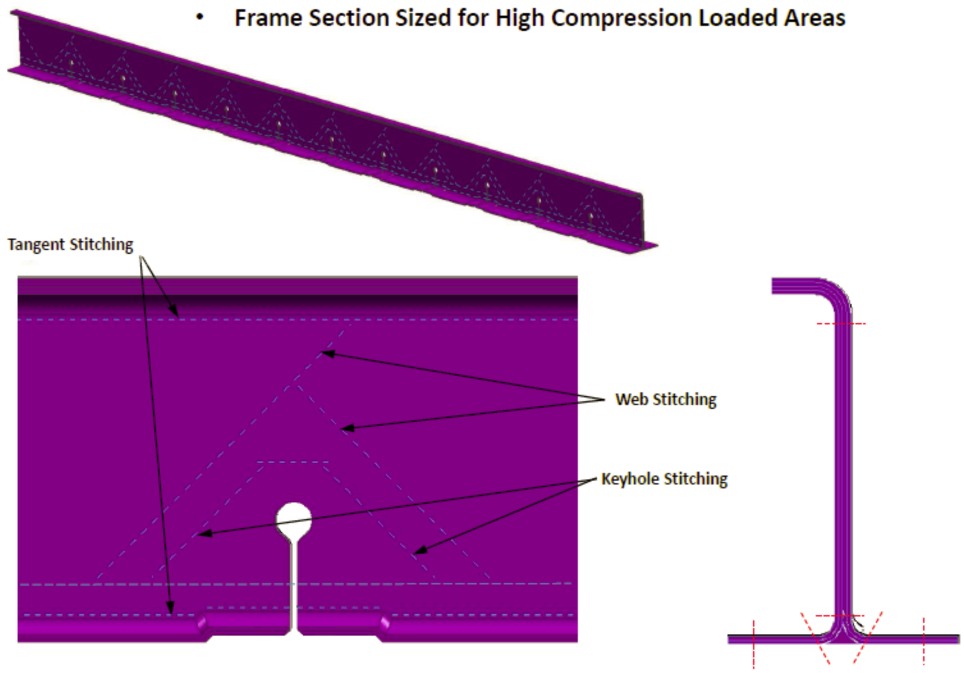


Figure 52. Constant Solid Frame with Web Stitching

The second solid frame is tapered and represents a frame that would be sized for a traditional tube-and-wing fuselage configuration. For this configuration, the frames are primarily loaded in bending so the web thickness was reduced to save weight. Web doublers were added at the keyhole region to reduce the stress at the reduced web cross section and around the keyhole itself. Stitching was again added around the keyhole, in the web, and along the stack drop-offs and radius tangents.

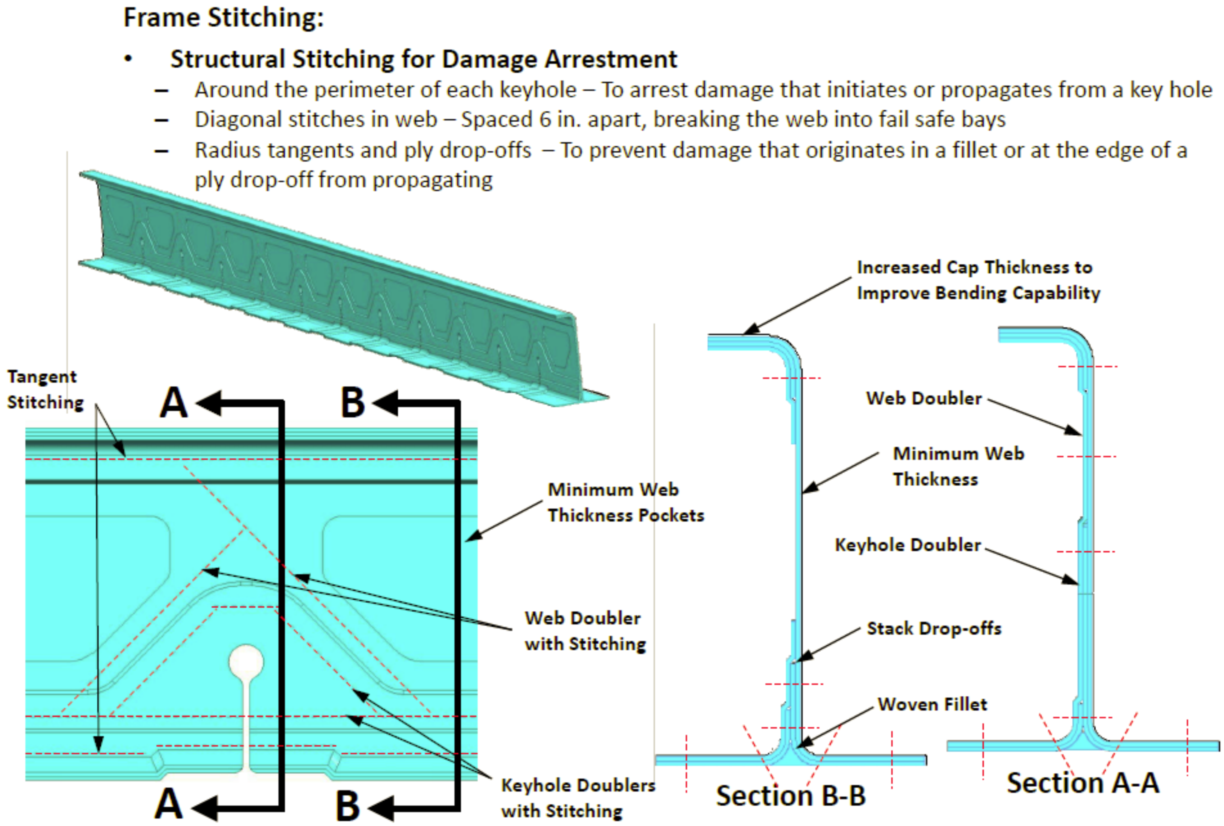


Figure 53. Tapered Solid Frame Design

A new stringer wrap stack was used on six of the eleven stringers. This new wrap is a 4 ply stack with 0/30/0/-30 stacking sequence. The stacking sequence increases the radial thermal expansion in the wrap around the rod and reduced thermal expansion along the length of the wrap to better match the unidirectional rod by eliminating the 90° hoop fibers and reducing the 45° plies to 30°. The angle between adjacent plies was reduced from 90° to 30° to decrease the transition stress in the matrix (resin) between plies. The areal weight per ply was reduced for thinner per ply-thickness, which also reduces the matrix stresses. The modulus of the laminate stack-up along the length of the stringer was increased by eliminating the 90° ply and reducing the 45° plies to 30° to better match the modulus of the rod. Increasing the modulus of the fibers (IMS65 E23, Toho Tenax-E 24K intermediate modulus fiber) in the wrap also helped to better match the modulus of the rod.

Adhesive was added to four rods to test the interface between the rod and the wrap. Currently, there is no evidence that indicates an adhesive interface is needed. This interface will be evaluated at hot and cold temperatures using the rod push out shear test.

Stitching in the webs of the integral caps was varied to understand how much stitching is actually required to increase the shear capability of the cap in bending. The layout of various features in the panel configuration is shown in Figure 54.

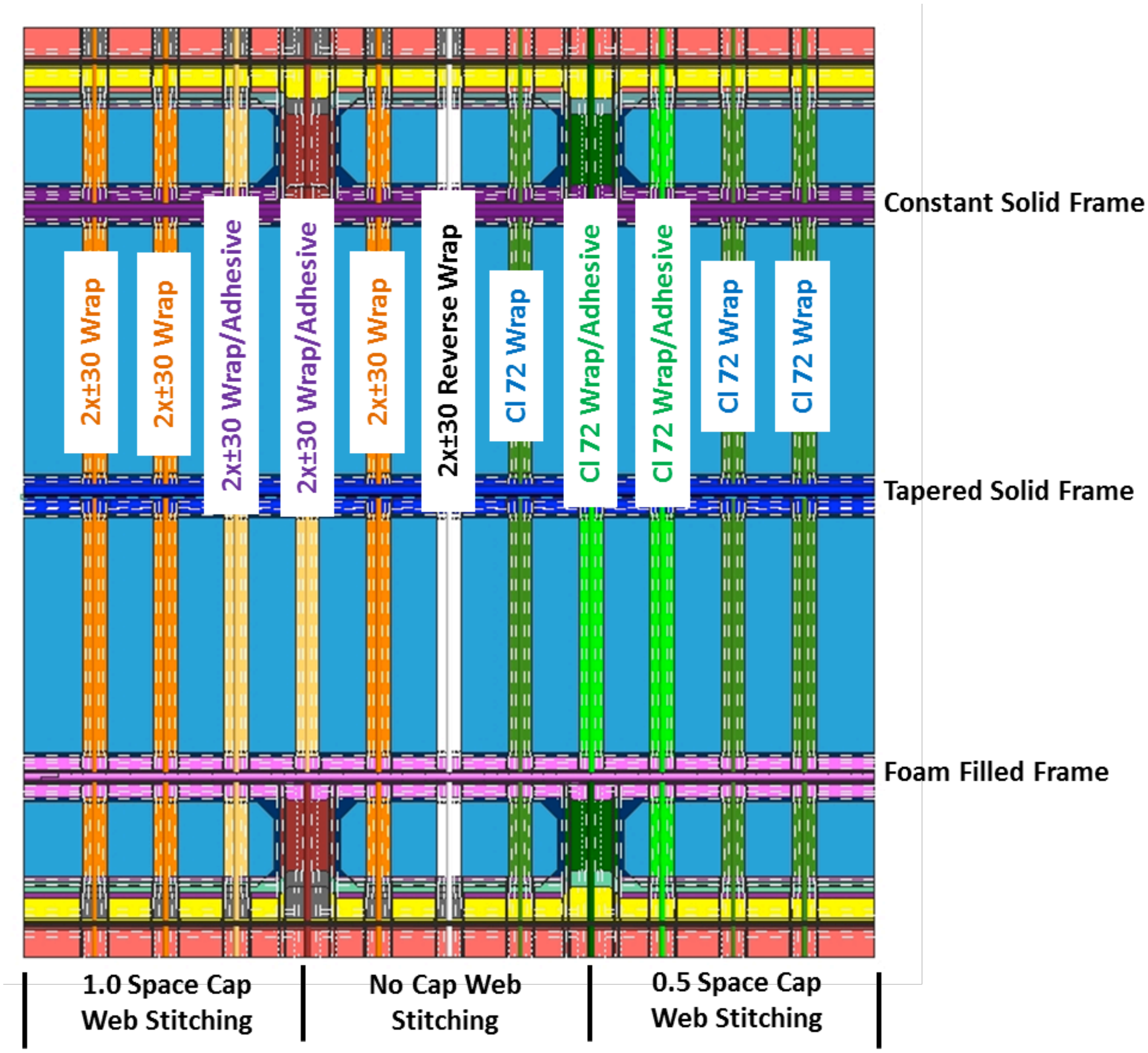


Figure 54. Alternate Center Keel Panel Layout

5.2 Tool Design

The design changes to the panel were done in a manner that would reduce the amount of tool changes. For the stitching assembly jig, in total, there were 22 blocks that were affected. The orange blocks in Figure 55 show the blocks that were replaced. The webs of the solid frames were shifted from the original frame locations, moving them away from each other to preserve the frame spacing in all but one bay. Thus, only ten blocks were replaced between the frames. The edge blocks were also replaced to compensate for the skin and frame doublers that were removed. None of the base blocks were replaced. Note that the base blocks are placed between the stitching blocks with all of the stitching grooves and the table to add additional height for the taller frame members. This configuration keeps the cost of the stitching block to a minimum. There are two small filler blocks that were required to reduce the foam core frame gap at each of the solid frame locations.

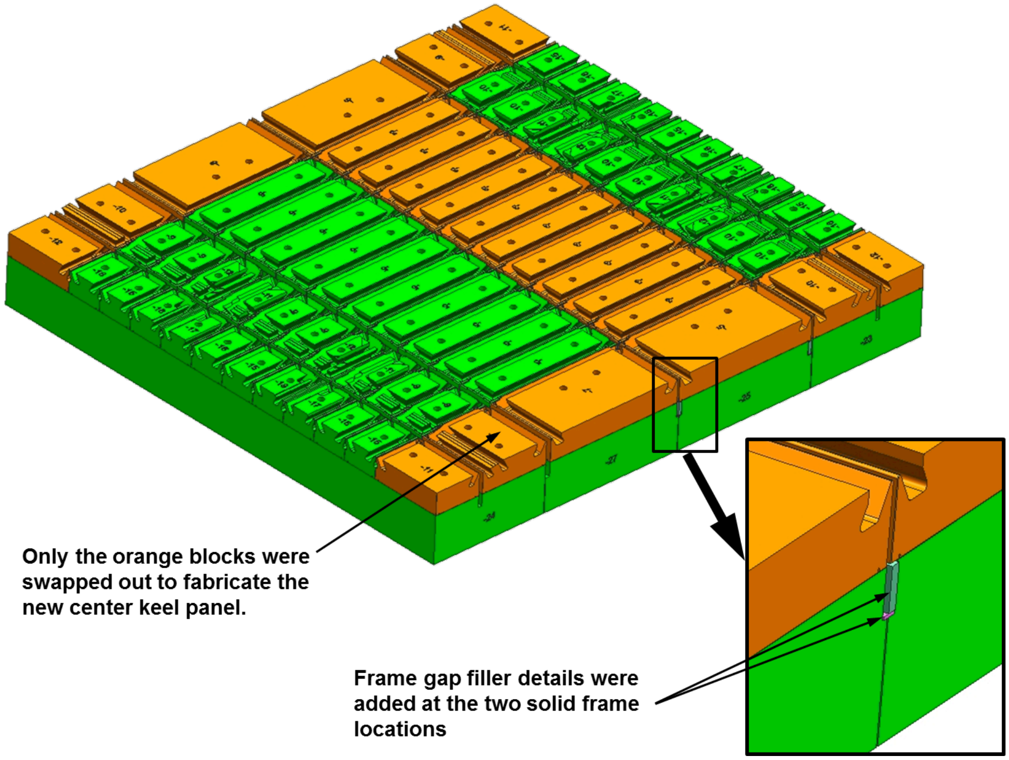


Figure 55. Stitching Assembly Jig (AJ) Modifications for Alternate Center Keel Panel

The solid frame configurations require tooling to support the frame preform during the cure process, unlike the foam-filled frames that are self-supporting. To evaluate different approaches for solid-frame tooling, two different configurations were used. A two-sided frame tool was used for the constant frame. This tool configuration is the easiest to vacuum bag over because all of the frame features were contained within the tool. It also formed both the back side and front side surfaces of the frame. The tapered frame utilized a one-sided tool. This frame is designed with all of the stack drop-offs on one (front) side of the frame. That meant that the tool used to form the other (back) side is flat without any joggles for stack drop-offs. This eliminated any fit-up issues that could arise if the edges of the stacks were not precisely located. The front side of the frame with all of the stack drop-offs for the web doublers, key-hole doublers, and the flange plies, was simply vacuum bagged. This insured that a constant and even pressure force would be applied to the entire frame eliminating any bridging due to tool fit-up issues. The entire cure tool concept used for this panel is shown in Figure 56. Besides the tooling used for the two new solid frames and the new stringer bagging aids between the two solid frames, the rest of the tooling remained unchanged from the original center keel panel, ZJ153356.

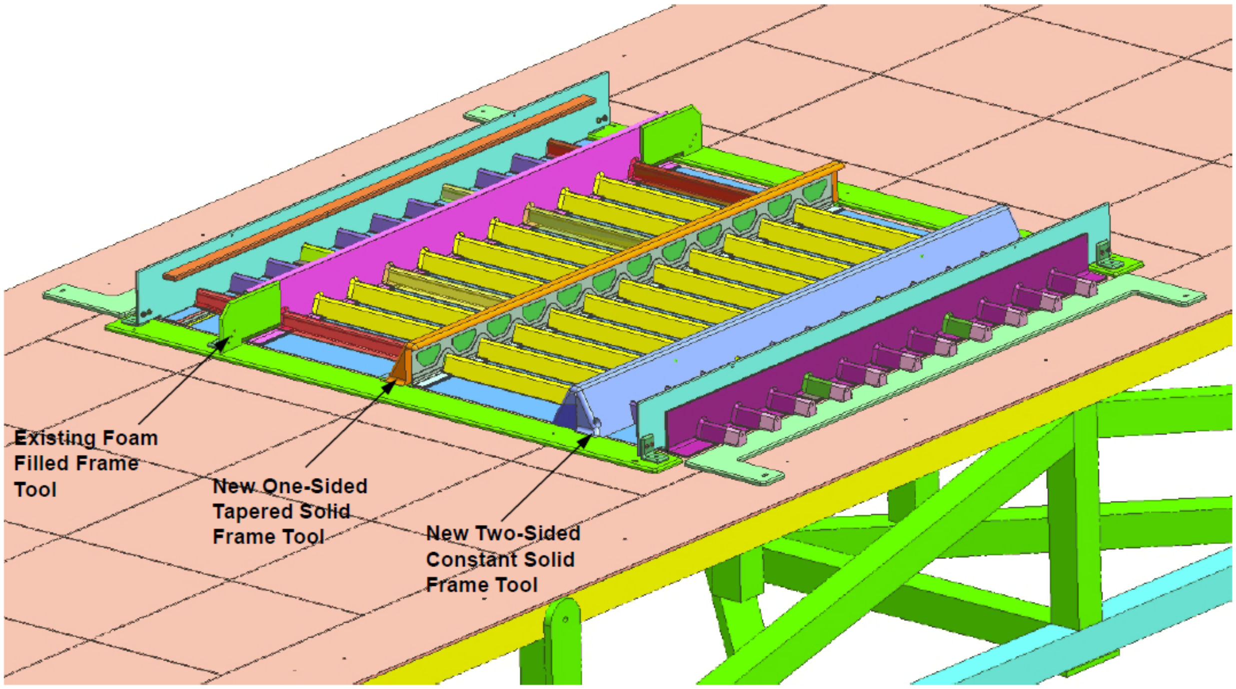


Figure 56. Cure Tooling for the Alternate Center Keel Panel

5.2 Fabrication

To gain some experience with fabricating a sold frame using hard tooling in place of self-supporting foam-filled frames, a smaller 'bench test' panel was included in the manufacturing plan to reduce risk for fabrication of the larger alternate center keel panel. The required tooling for the bench test was already available. The bench test panel measured about two feet by three feet and had a single solid frame with six stringers. The bench test provided a manufacturing trial for creating the solid frame preform, assembling the frame to the panel, supporting a frame using hard tooling, and completing resin infusion processing.

The stitched solid frame preform detail is shown in Figure 57. Stitching around the keyholes where the stringers web and bulb pass through the frame web, stitching in the frame web and stitching at the radius fillet were all added to the frame preform.

Figure 57. Stitched Solid-Frame Detail and Stitching Pattern Around Keyholes

Figure 58 presents a series of photos showing the assembly of the preform in the stitching assembly jig (AJ). The solid frame is the first detail to be loaded into the AJ. Next, the stringers details are loaded into the AJ which positions the stringers in the keyhole slots in the frame webs. Rods are then drawn through pre-stitched pockets in the top of the stringer details. Stringer and frame tear straps are then located over their respective flanges. The skin is then positioned on the AJ to close out the preform assembly. Using the one-sided stitching head, the frame and stringer along with the tear straps are now stitched to the skin. The completed preform is shown in Figure 59.

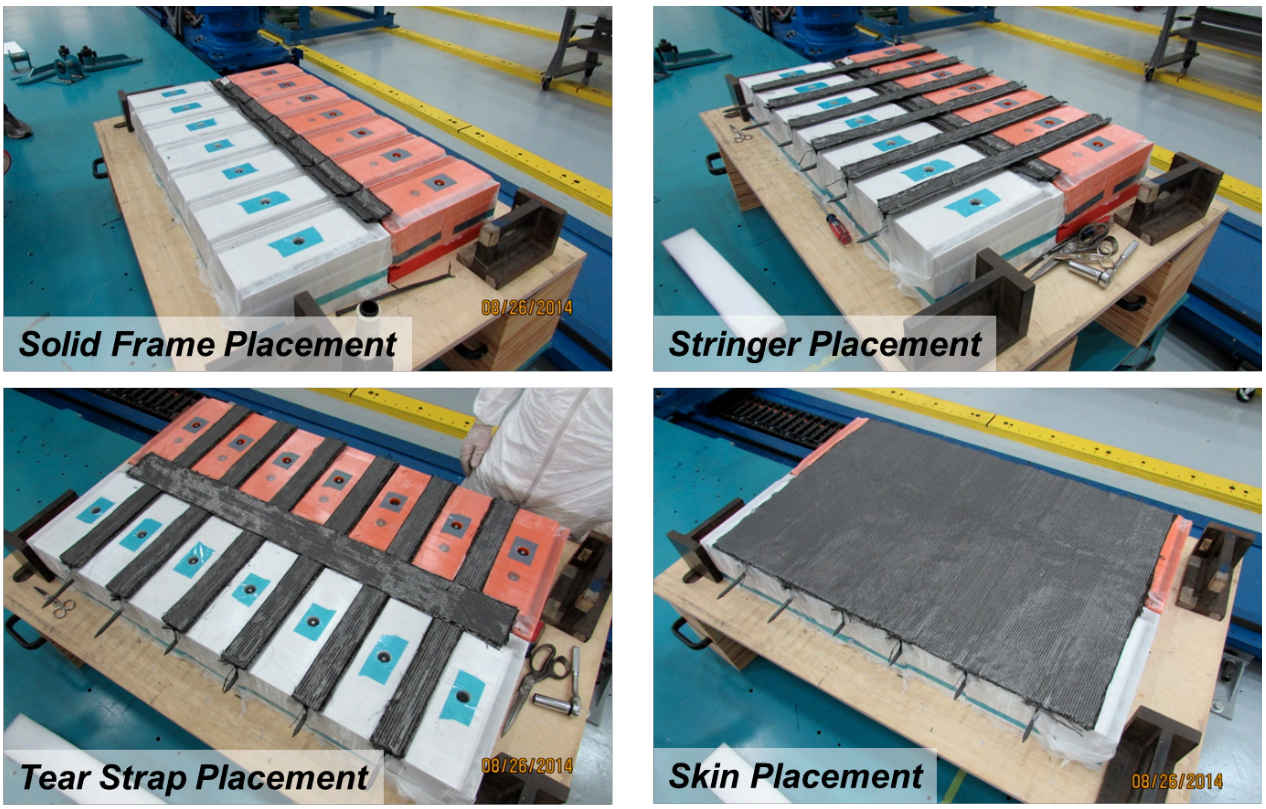


Figure 58. Preform Assembly for the Bench Test Article

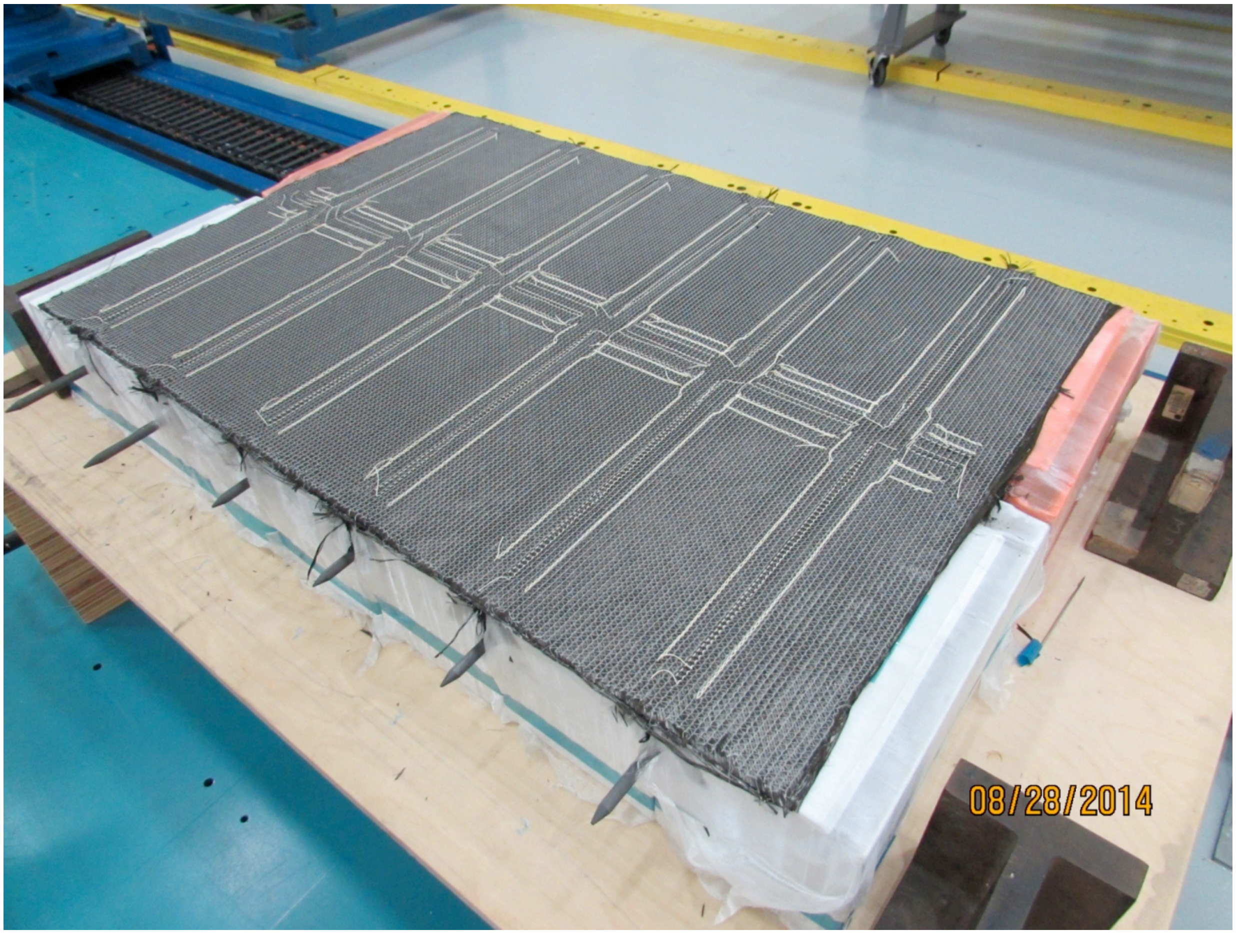


Figure 59. Stitched Preform for the Bench Test Article

The preform stitching went relatively smoothly. The AJ blocks for the bench test were made (prior to this task order) by three-dimensional (3-D) printing, allowing the tooling to be procured quickly. 3D printing takes a solid model from the tool designer, loads it into the 3D printer machine and produces the AJ block within hours. However, these AJ blocks are rigid, and are not as forgiving as foam blocks if the stitch lanes are mis-located or not deep enough. The AJ tool did work very well supporting the solid frame preform and stitching the frame flanges went smoothly. The next steps were transferring the preform to a cure tool table, and installing the IML cure tool details that support the solid frame and stringers during vacuum bagging and curing of the panel. These steps are shown in Figure 60. The completed part being de-bagged and de-tooled after resin infusion processing is shown in Figure 61.

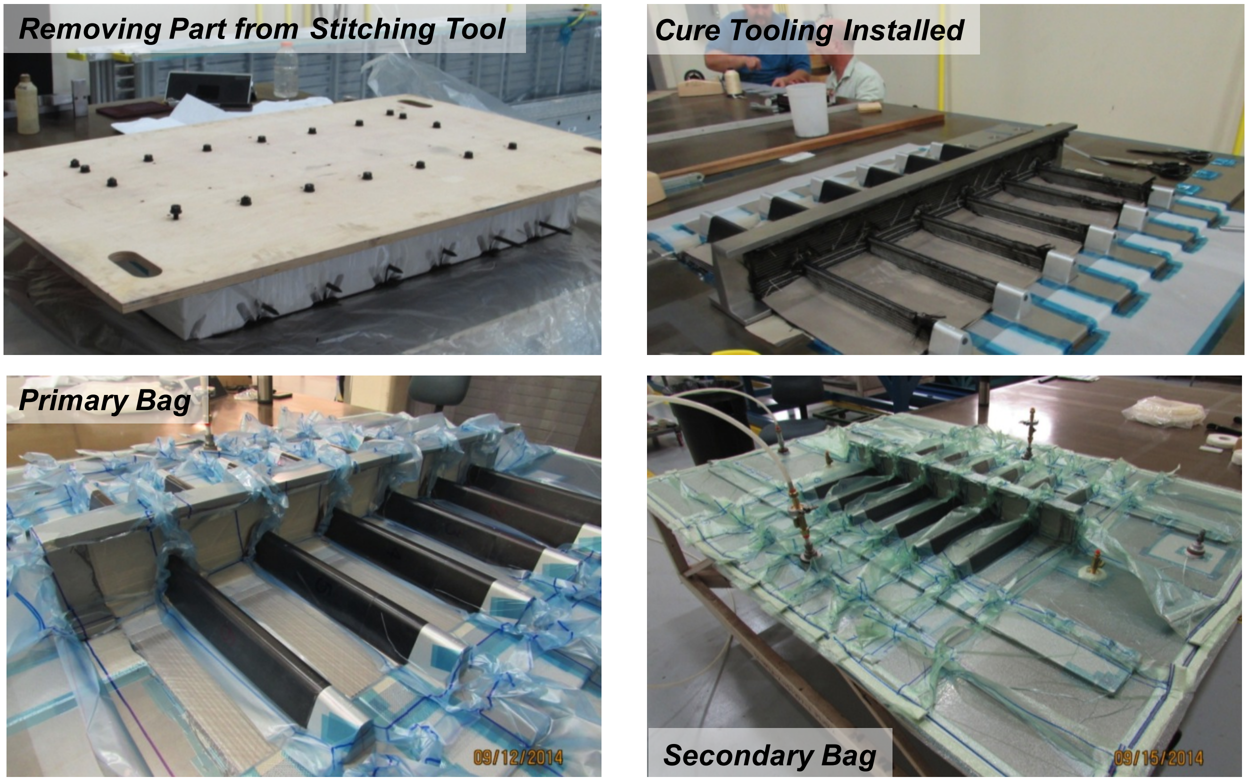


Figure 60. Infusion Preparation for the Bench Test Article

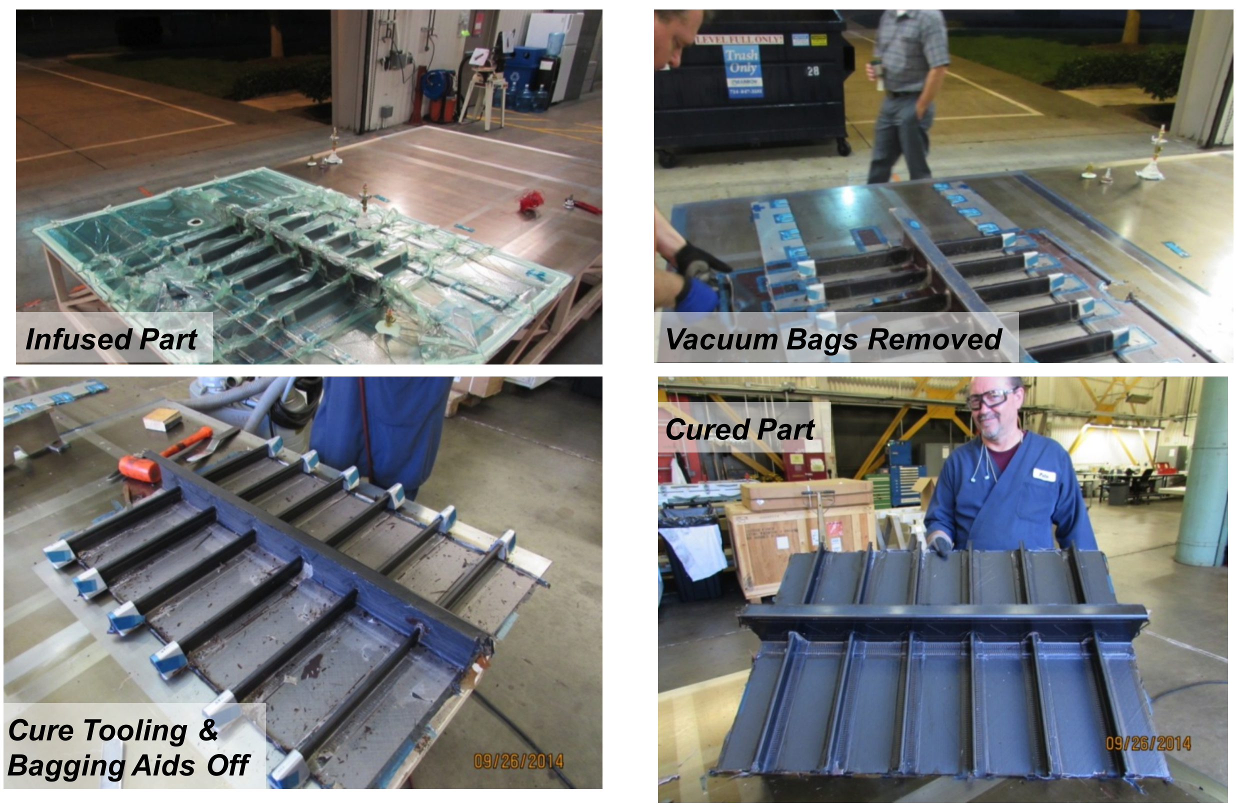


Figure 61. Completion of Resin Infusion Processing for Bench Test Article

The completed bench test panel after clean-up is shown in Figure 62. The panel geometry was well formed, and the solid frame overall was straight. There were no resin starved areas indicating any problems with resin flowing along the frame surface during infusion process. Only one issue was identified at locations where the stringers pass through the frame web. At these intersection locations, the ends of the silicone bagging aids located on both sides of the solid frame web applied the compaction pressure required to produce a void free laminate. Because the only resistive pressure being applied to the bagging aid was the bagging aid on the other side of the frame web, if one bagging aid expanded a little more than the opposing bagging aid, the solid frame web would be distorted. During the resin infusion process, this is exactly what happened. The bagging aid on one side pressed against the web a little more than the other and pushed the solid frame web out of plane locally. The outlines of the affected regions can be seen in the lower right photo in Figure 62.

For the alternate center keel panel, the solid-frame mold tooling, described in the previous section, was redesigned to support the bagging aids so they would not press directly against the frame. The bench test was a worthwhile effort to improve and refine the fabrication tooling for the solid frame configuration.

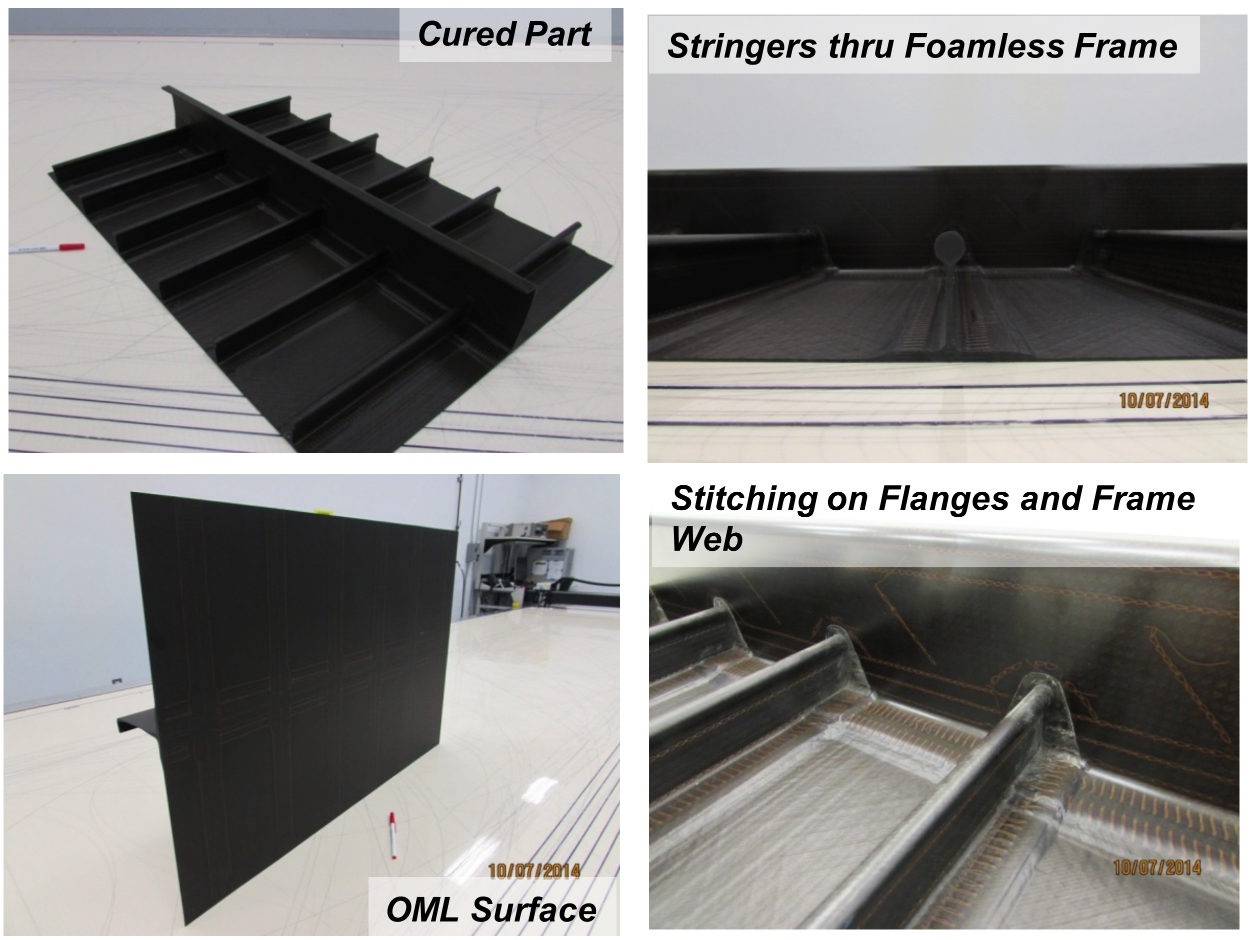
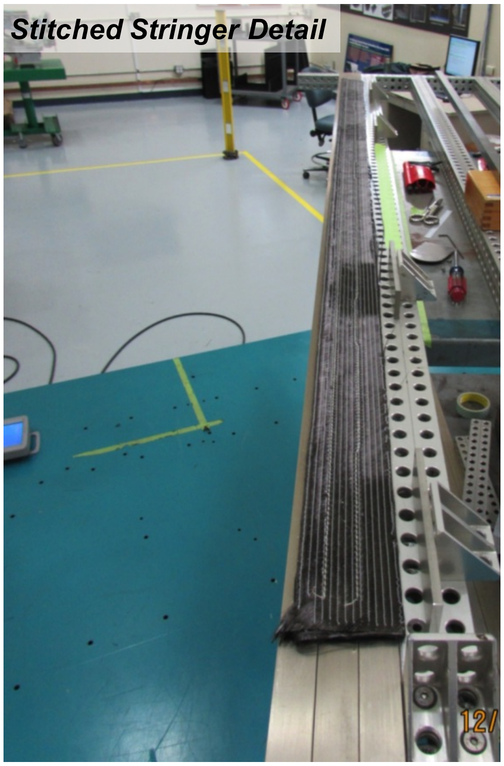


Figure 62. Features of Bench Test Article

By the time fabrication of the panels for the MBB assembly was completed, various improvements had been made in the stitching center at Boeing, and the alternate center keel panel was fabricated using some new equipment. The stringer and frame preform details were stitched using a new two-sided stitching head. The set ups for a stringer detail and the constant solid frame detail are shown in Figure 63. Stitching of the tapered solid frame detail is shown in Figure 64. The new stitching head is visible in the upper right photo in Figure 64.



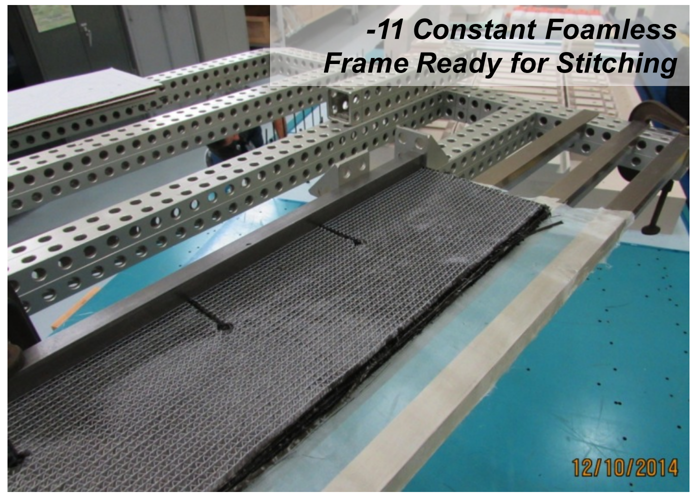


Figure 63. Fabrication of Stringer and Solid Frame Details for the Alternate Keel Panel

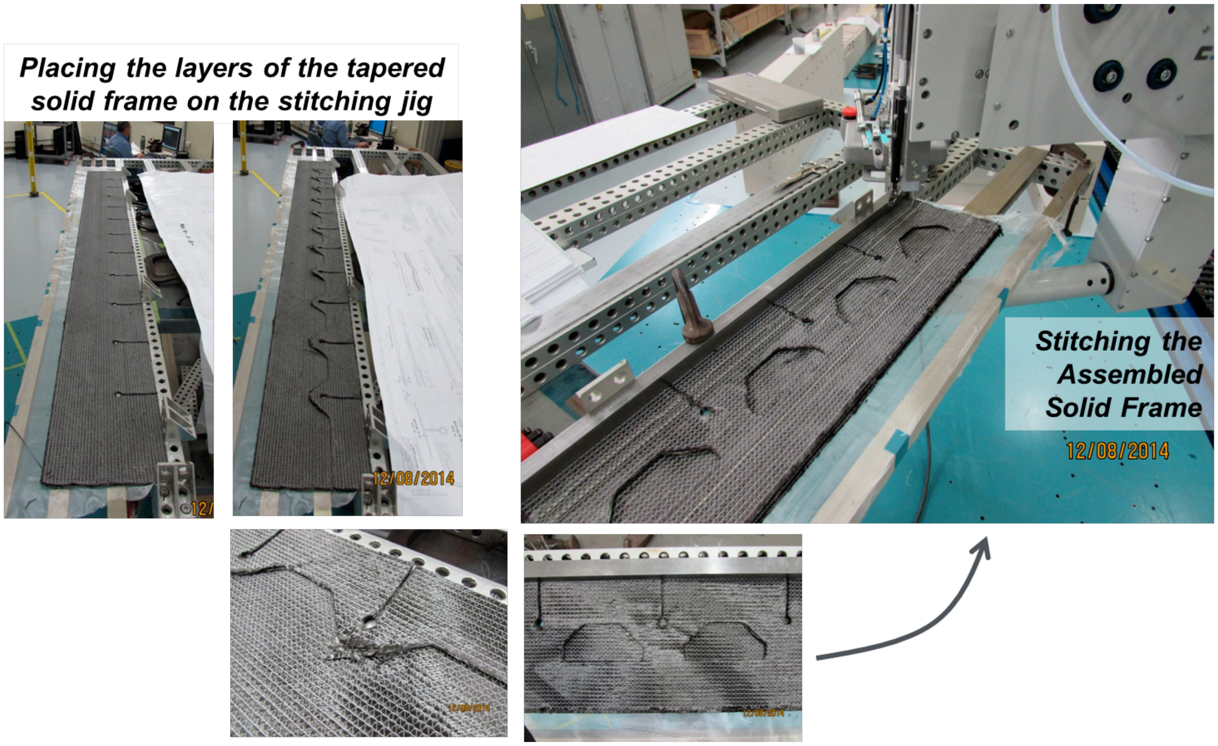


Figure 64. Fabrication Step for the Tapered Solid Frame Preform Detail

The details were inserted into the AJ similar to the other MBB panels. The only differences relative to the center keel panel of the MBB were the modified AJ tooling blocks, described in the previous section, and the solid frame details for two of the three frames. The details being loaded in the AJ are shown in Figure 65. All of the preform details in place are shown in Figure 66.

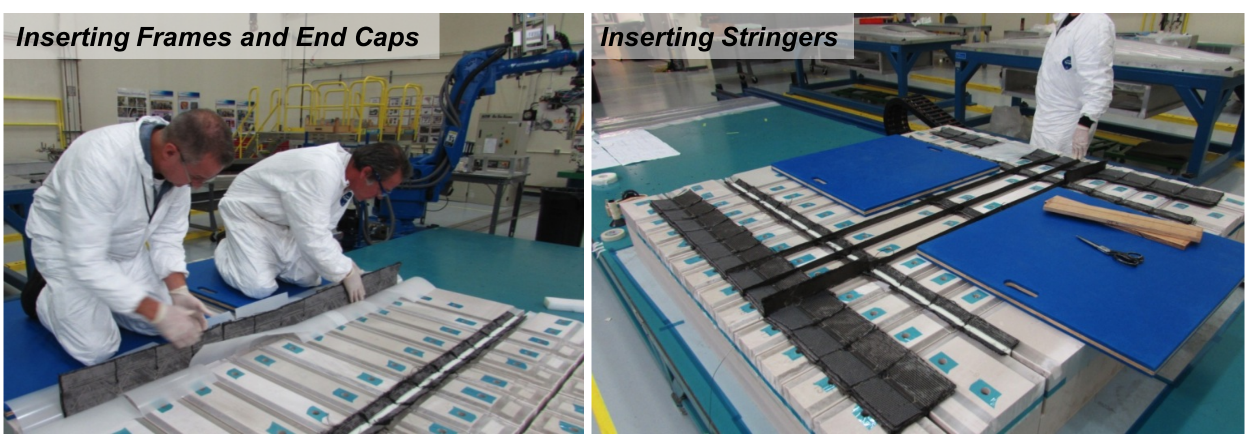


Figure 65. Preform Assembly

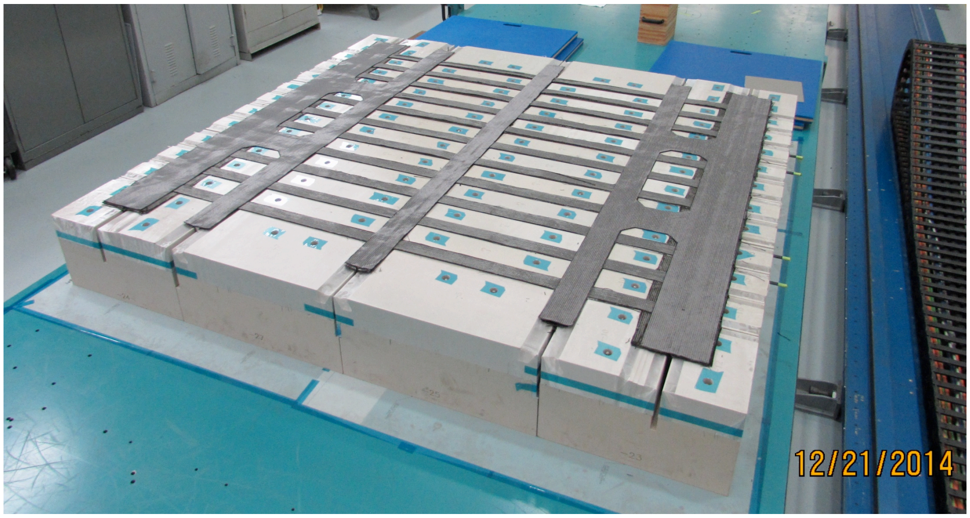


Figure 66. Preform Details Placed in Assembly Jig

The next step was placement of the skin stack on the AJ. The only difference between the original center keel panel and the alternate center keel panel was that the skin and frame doublers on the side edges of the panel were not present. The completed preform, after assembly stitching, is shown in Figure 67.

Four of the 11 stringers in the panel were coated with adhesive, as previously described. Due to out-time limitations for the adhesive, temporary rods without an adhesive coating were used during the preform assembly process. Once the preform was transferred over to the cure table, the bare rods in the preform were replaced with adhesive coated rods as shown in Figure 68.

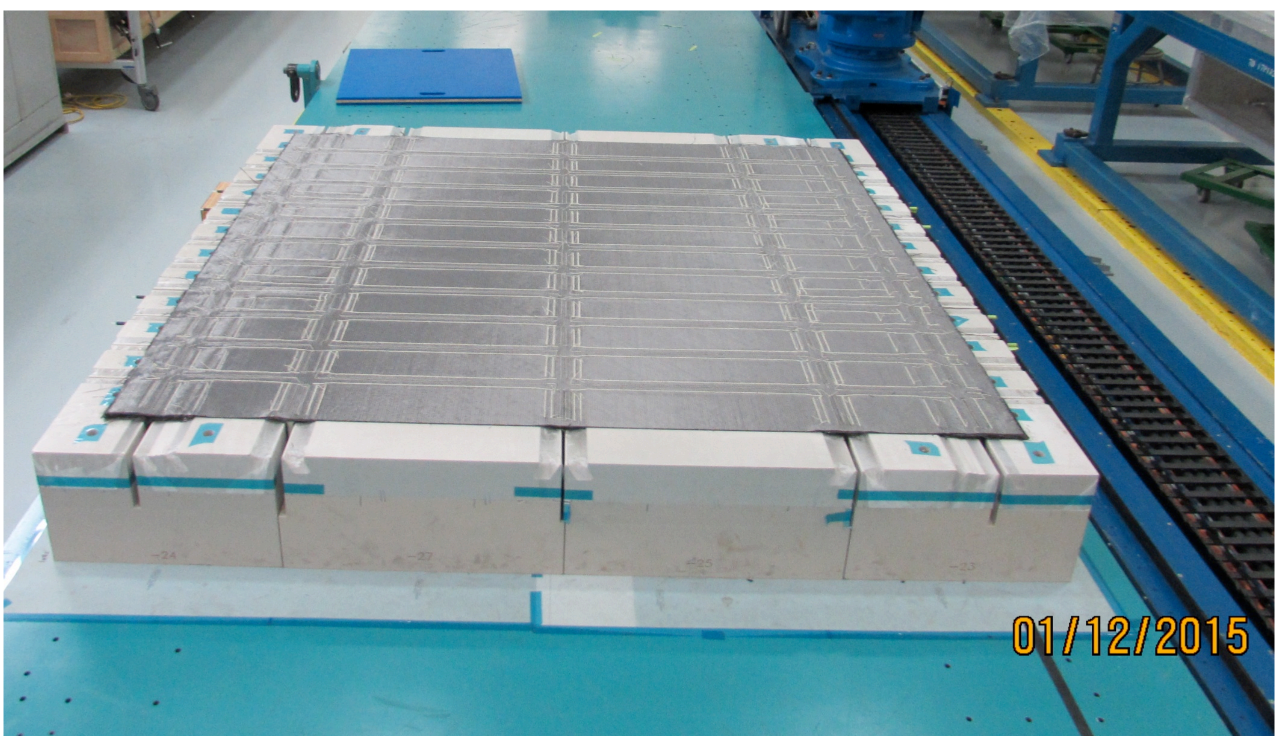
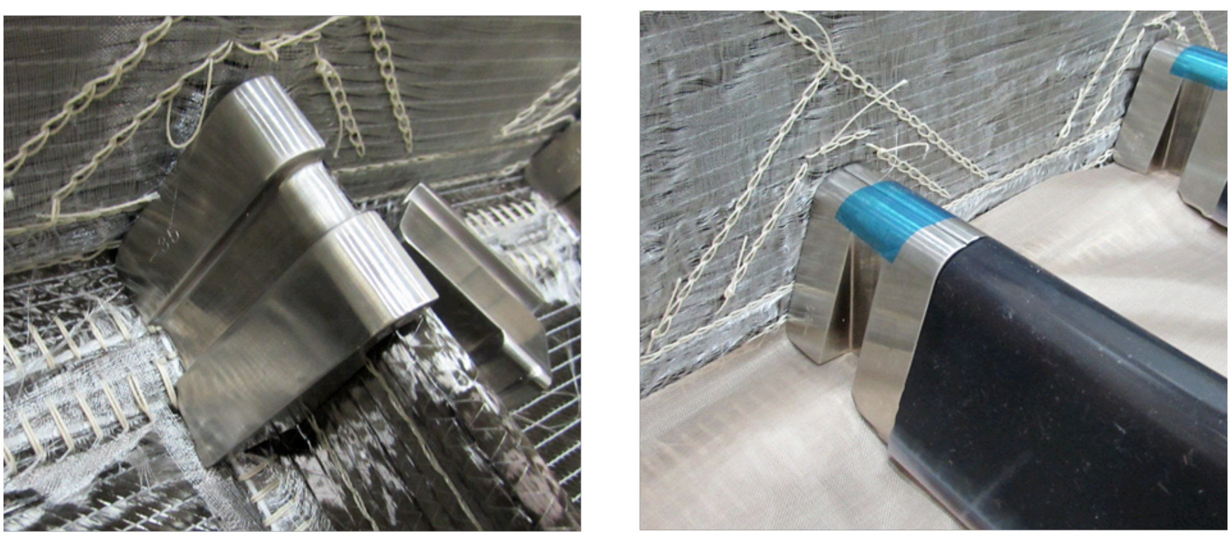


Figure 67. Completed Preform Assembly

Figure 68. Insertion of Adhesive-Coated Rods

With the preform completed, the IML cure tools were installed (Figure 69). Installation of the new solid frame hard tooling for both solid frames went smoothly. The upper right photo in Figure 69 shows the new tooling concept at locations where the bagging aids distorted frame web locally on the bench test panel. The hard IML frame tools used for the alternate center keel panel prevent this from happening. A separate detail indexed to the main tool forms the stringer shape directly under the tool and creates a continuous surface for the entire frame web to be formed against. The index feature is shown in the upper right picture in Figure 69. With these small details locked in place, thermal expansion of the bagging aid during the infusion process did not affect the frame web shape. Two different locking features were tried (Figure 70). The first one was a shallow constant engagement that wrapped all around the interface. The second one was a tapered engagement only on the side. Both locking features released very well and had no issues. However, the side locking feature was easier to machine and will be the method going forward. The two lower photos in Figure 69 show the two-sided tooling for one of the solid frames being installed. First, the inside tool was located against the frame preform. The top cap of the frame was then positioned over the tool and the outer side tool was locked into position by the side rails. The various frame configurations and all of the IML cure tools required to fabricate the alternate center keel panel are shown in Figure 71. From left to right, the constant solid frame used a two-sided support tool, the tapered-thickness solid frame used a one-sided tool, and the foam-filled frame was tooled just at its ends that control just the splice locations (as in the previous MBB panels). The integral caps had one-sided support tooling along their entire lengths (as in the previous MBB panels).

Figure 69. Installation of IML Tooling



Wrap Around Locking Feature **Side Locking Feature**

Figure 70. Solid Frame Stringer Details

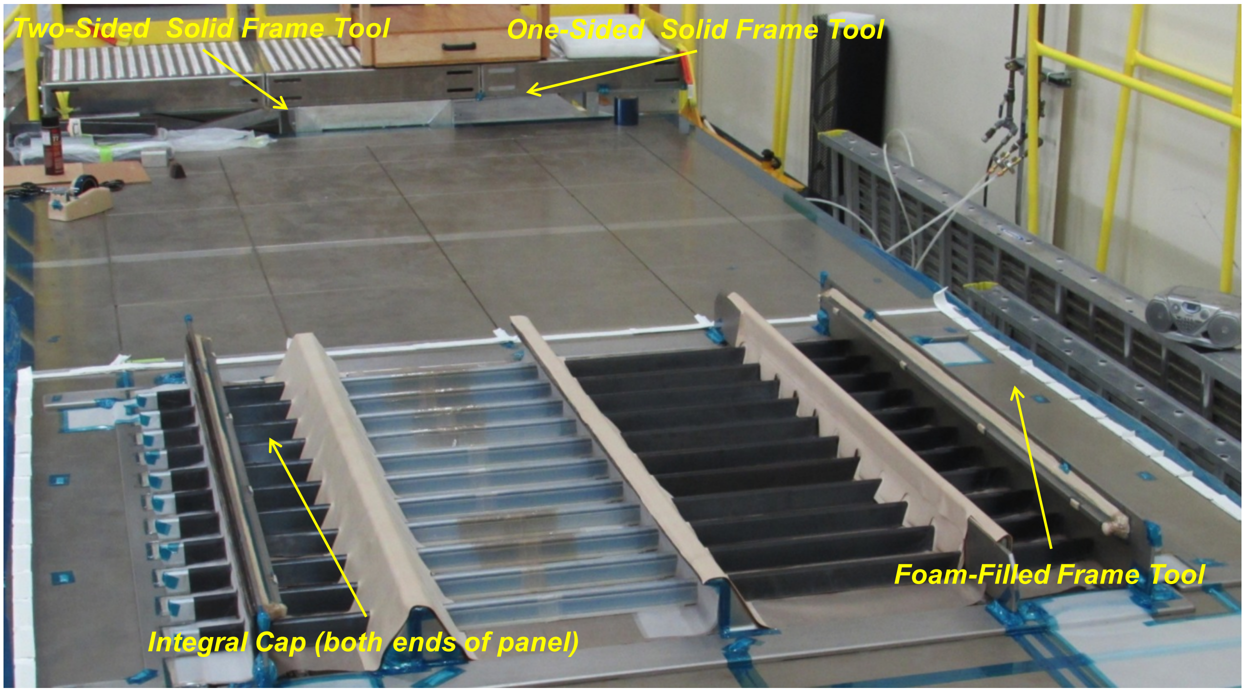


Figure 71. Preform with IML Tooling Installed

After installation of IML cure tools, the preform was vacuum bagged for infusion. Primary and secondary bags were installed, as shown in Figure 72.

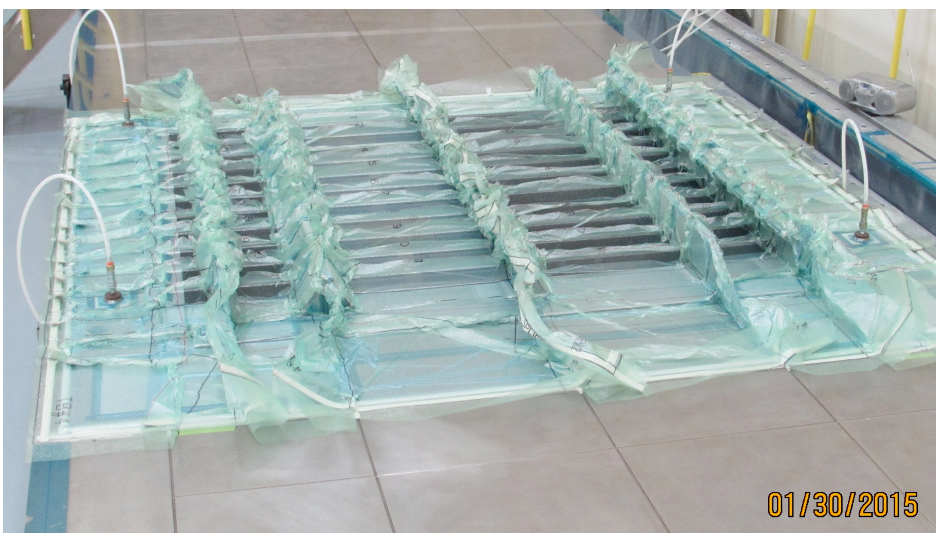


Figure 72. Preform Bagged for Infusion

After resin infusion processing, the vacuum bags were removed and post cure was completed. The IML cure tools were then removed, and the panel was cleaned up for inspection. The completed panel after initial cleanup is shown in Figure 73 and Figure 74. Final panel trim will be accomplished by NASA.

Figure 73. Completed Alternate Center Keel Panel with Initial Edge Clean-up

Figure 74. Doublers, Frames, Caps, and Stringers on the Alternate Center Keel Panel

5.3 Inspection

A visual inspection was performed on the cured panel and documented in Nonconformance Report #00989 (delivered to NASA along with the panel). Overall, the cured panel looked very good. No porosity or resin starved areas were found. All three frame configurations and both caps were straight and perpendicular to the skin. There were no gaps between a straight edge and the frame and cap webs as shown in Figure 75. The upper flanges on the solid frames were 90 degrees to the frame webs. All of the stitching in the panel and the new stitching in the frames looked good. Directly under the solid frame hard tooling, the OML skin surface developed shallow wrinkles between the stringer flanges. The wrinkles on one side of the tapered solid frame that used hard tooling on one side are shown in Figure 76. The frame hard tools have a height stop at the base of each end that controlled the frame flange thickness. The slightly darker area on the panel indicates a resin rich area compared to the adjacent areas. This slightly darker area indicates that the stops were too tall and did not allow the tool to fully compress the flanges of the frames allowing the OML surface to wrinkle. Wrinkles in the OML surface were also along the edges of some of the stringer edges. If the stringer bagging aids overhang the stringer flanges, a gap is formed under the edge of the bagging aid. When the vacuum bag cannot apply pressure to this strip of panel under the edge of the bagging aid, the skin can form wrinkles on the OML surface.

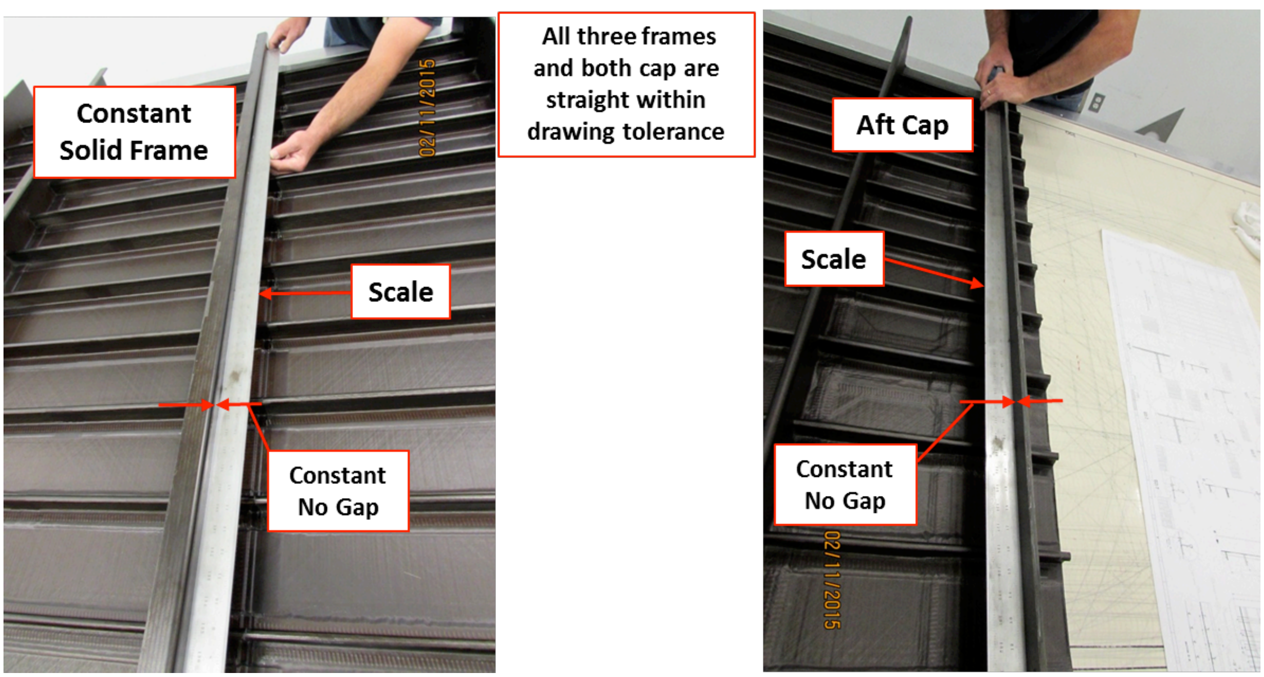


Figure 75. Frames and Cap Webs were Straight on the Cure Panel

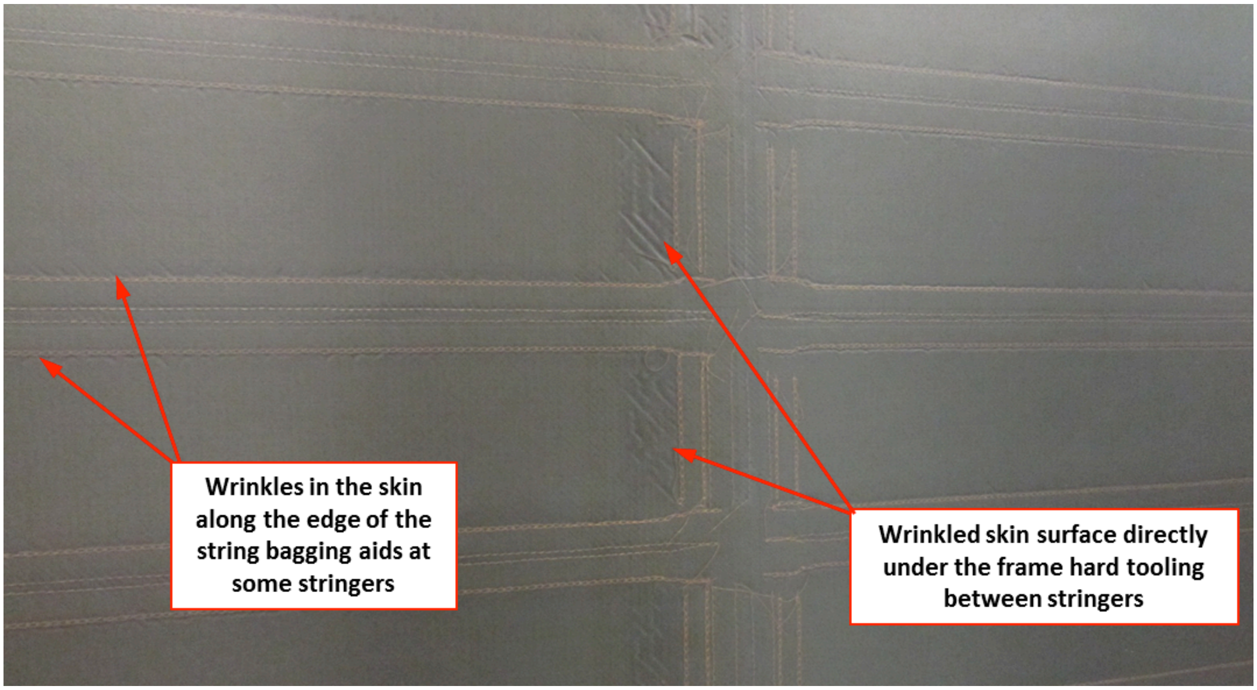


Figure 76. Wrinkles in the OML Surface

Some simple OML flatness measurements were taken using a straight edge. The results of this check are shown in Figure 77 and Figure 78. In the frame direction directly over a cap or frame, the panel was flat. Mid-bay between frames, the panel is flat across the stringer locations, but has a slight bow (inward towards the IML) between the stringers with a tapering gap maximizing at 0.028 in. (typical). In the stringer direction, there is an overall bow (inward towards the IML) in the panel with a maximum depth of 0.35 in.

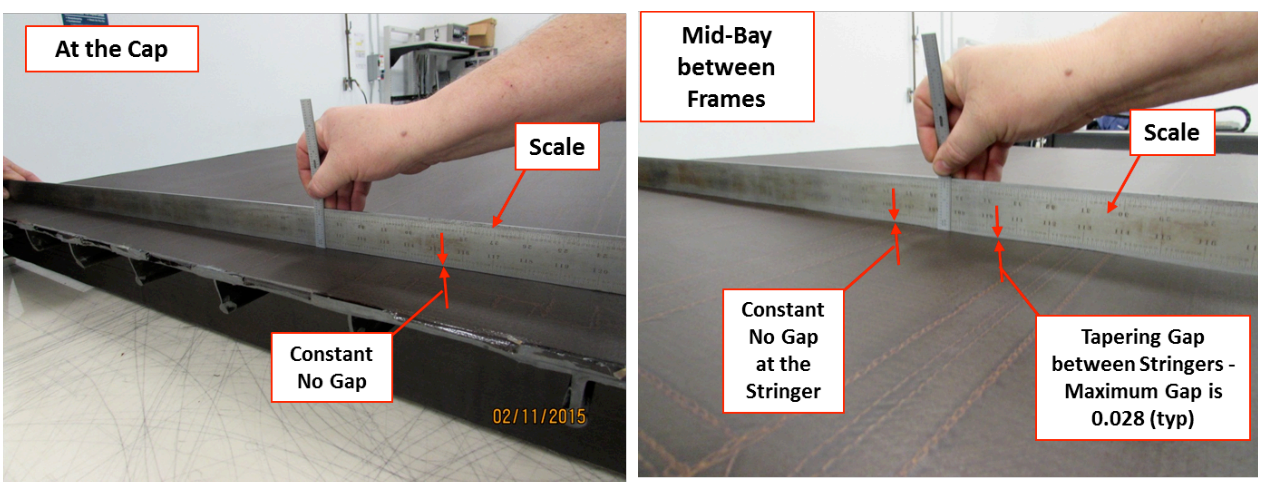


Figure 77. OML Surface was Flat in the Frame Direction

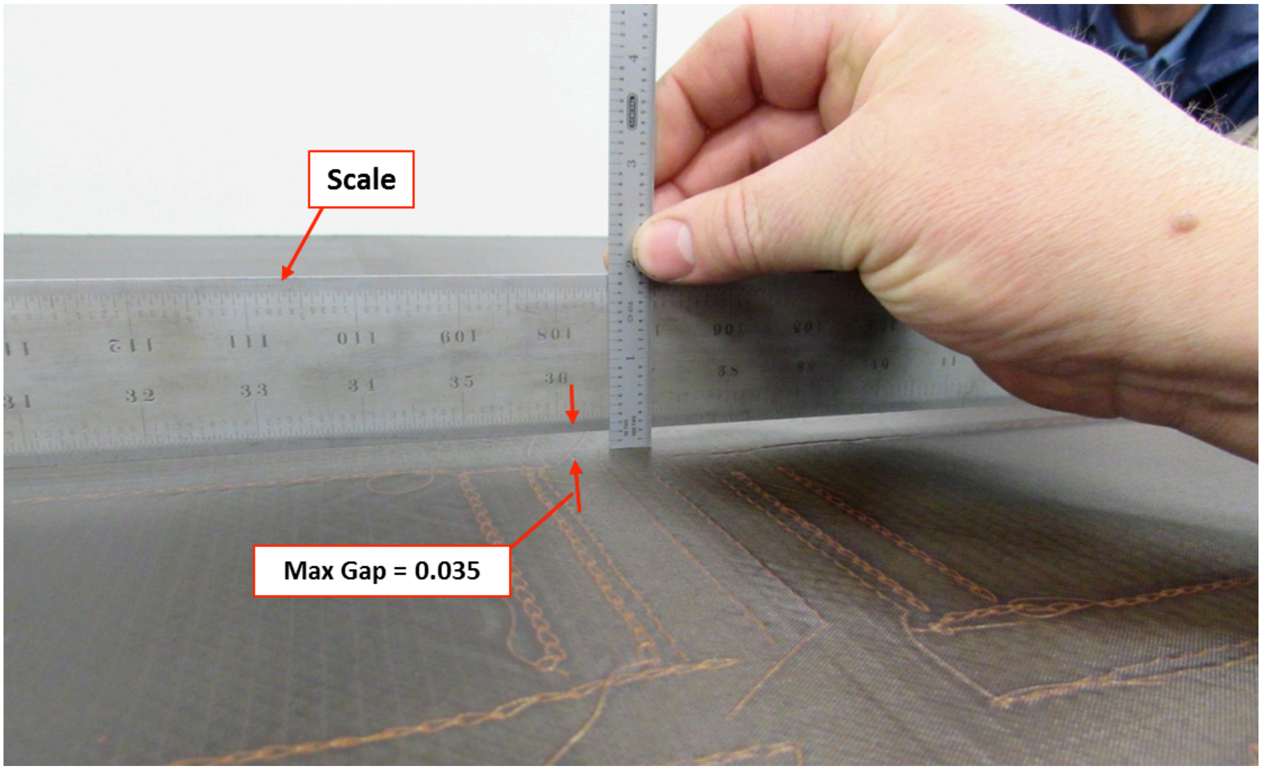


Figure 78. OML Surface had an Overall Arcing Bow in the Stringer Direction

5.4 Test Plan

If the alternate center keel panel were not needed for repairs on the MBB, plans were made to extract specimens from the panel for testing. A map of the specimens that could be trimmed out of the panel is shown in Figure 79. This array of specimens will look at several features of the panel. In all, there would be 12 single frame compression specimens, 10 single stringer compression specimens, 30 bulkhead cap specimens that could be tested in bending, tension and/or combined bending and tension and 128 rod push-out shear specimens.

With the alternate center keel panel intact, the OML would be geometrically inspected to determine the as fabricated panel shape. NASA has been conducting thermal distortion analysis and will be correlating the predicted panel shape to the as fabricated shape. The six stringers with the new wrap layup were grouped on one side of the panel, so the thermal distortion effects of the different stringer wraps could be determined.

Once the distortion activies have been completed, the panel would be cut up into test specimens for structural testing. The single frame specimens evaluate the compression strength of the three different frame configurations. The results from the foam-filled and constant-thickness frames can be directly compared in compression. The foam-filled frames were originally designed to be able to support the high compression loads that a HWB aircraft configuration imparts on a frame member. With some additional tooling, can a weight efficient solid frame be designed to support these high compassion loads? The tapered frame was designed more for a tube and wing configured aircraft that are dominated by bending loads. It was designed with a light weight web and reduced upper cap thickness. Therefore, the tapered frame compression strength will not directly compare to the other two frame configurations.

Several single stringer compression specimens are included in the plan. Half of the stringers were fabricated with a new 0/30/0/-30 stack wrap. The remaining stringers were fabricated using the existing Class 72 wrap. One stringer rod with each wrap type was coated with a layer of adhesive to see if an adhesive interface affects the load in the wrap. One set of the new 0/30/0/-30 stack wrap was reversed to see if a 30° ply in the wrap adjacent to the 0° fibers in the rod is better or worse than a 0° ply in the wrap adjacent to the 0° fibers in the rod.

A number of integral cap specimens will be tested in bending, tension (pull off) and combined bending and tension tests to examine the fillet strength and how much stitching in the web is needed to increase the shear strength of the web.

The last type of testing that could be performed with this panel is the rod push-out shear test. The remaining stringer segments could be environmentally tested at hot and cold temperatures, with and without impact damage, and with and without an adhesive interfaces.

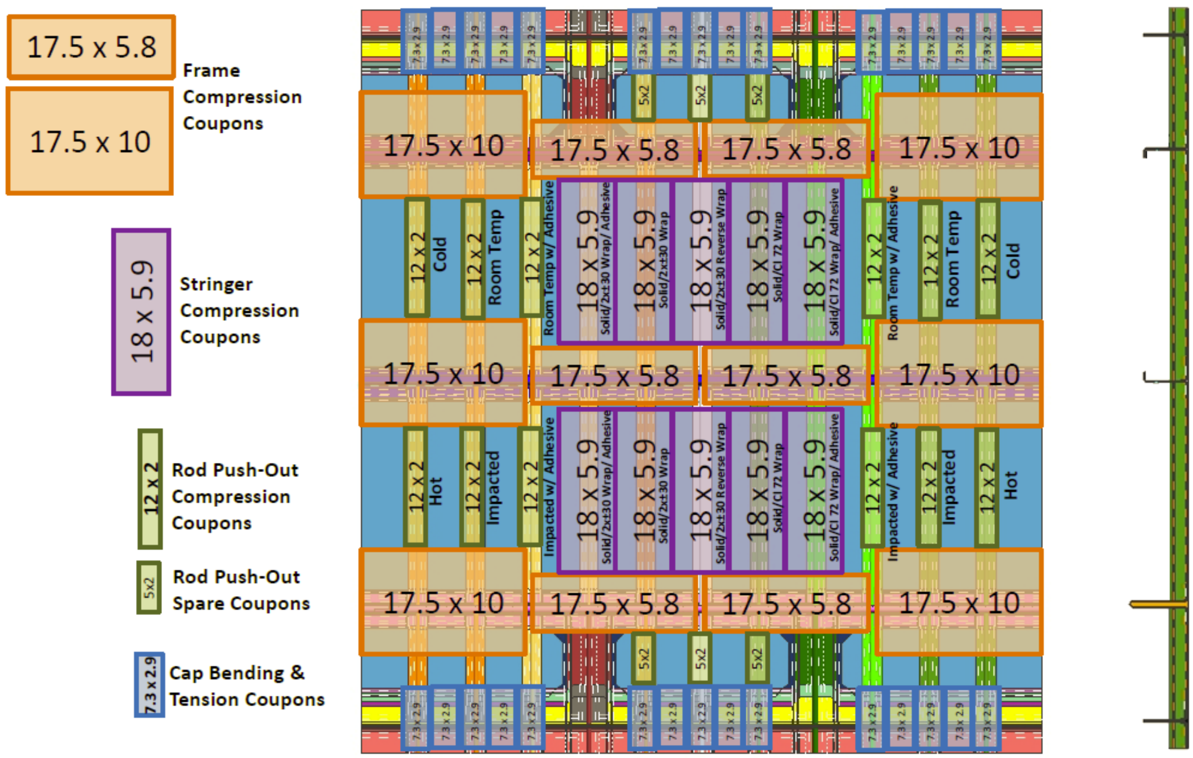


Figure 79. Specimen Map for Alternate Center Keel Panel

Summary and Conclusions

Under this task order, the last panels for the MBB were completed and delivered for the lower section assembly effort. The delivery times supported the MBB assembly schedule. The specific fabrication tasks completed were: 1) edge trimming and inspection for the cured lower bulkhead panels, and 2) panel build up starting with preform assembly for the side keel panels and center keel panel. All of the panels fabricated had the required quality for use in the MBB assembly. As panel fabrication progressed, the fit and finish of the panels improved, and each successive panel required less shimming work during the MBB assembly.

In addition to the MBB panels, an alternate center keel panel was fabricated as a risk reduction article, in the event of damage to the MBB requiring a structural patch. This panel incorporated some new features, such as solid frames with tapered and constant cross sections, adhesive-coated rods, and a new layup for the stacks wrapping the rod forming the stringer. The fabrication of these features was successfully demonstrated, paving the way for them to be used in future structures.

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14. ABSTRACT
NASA and the Boeing Co. have been working together under the Environmentally Responsible Aviation Project to develop stitched unitized structure for reduced weight, reduced fuel burn and reduced pollutants in the next generation of commercial aircraft. The structural concept being evaluated is PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure). In the PRSEUS concept, dry carbon fabric, pultruded carbon rods, and foam are stitched together into large preforms. Then these preforms are infused with an epoxy resin into large panels in an out-of-autoclave process. These panels have stiffeners in the length-wise and width-wise directions but contain no fasteners because all stiffeners are stitched to the panel skin. This document contains a description of the fabrication of panels for use in the 30-foot-long Multi-Bay Box test article to be evaluated at NASA LaRC. The document also describes a panel which explores new PRSEUS concepts for applications beyond the Multi-Bay Box.

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